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Uniting Deep-Sea Coral with Geomorphology

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Uniting Deep-Sea Coral with Geomorphology

A Major Individual Project submitted in partial satisfaction of the requirements
for the degree of Master of Science in Geographic Information Systems

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The report of Jason Greenstein is approved.

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Abstract

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by
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The Deep Sea Coral Research and Technology Program manages an online database containing deep-sea coral records. However, their data lacks standardized information about which seafloor feature each coral is located on, a factor which greatly influences their distribution. The goals of the project were to (a) enrich the Program's deep-sea coral data with coincident geomorphic features, and (b) classify slope position zones for the Eastern U.S. Exclusive Economic Zone (EEZ). A standardized and authoritative seafloor geomorphic feature set of 24 feature classes was spatially joined to the coral data and can be used in the Program's online database. Then, five slope position maps of the Eastern U.S. EEZ were produced using five different neighborhood sizes of topographic position index. Areas of gradual elevation change were not adequately classified while areas of stark elevation change were accurately classified. The standardized global geomorphic features, along with slope position zones, can be used in deep-sea coral habitat models to better elucidate the spatial distribution of coral to develop more effective conservation strategies.

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List of Acronyms and Definitions

BPI	Benthic Position Index
GIS	Geographic Information System
GSGF	Global Seafloor Geomorphic Feature
NOAA	National Oceanic and Atmospheric Administration
SRTM	Shuttle Radar Topography Mission
TPI	Topographic Position Index
UML	Unified Modeling Language

Chapter 1 – Introduction

Housing a great abundance and diversity of species, coral reefs are among the most productive ecosystems on Earth. Although coral is typically affiliated with shallow waters, they also inhabit deeper regions of the ocean; deep-sea coral characterizes species living at depths of 50 meters and below (Figure 1-1).

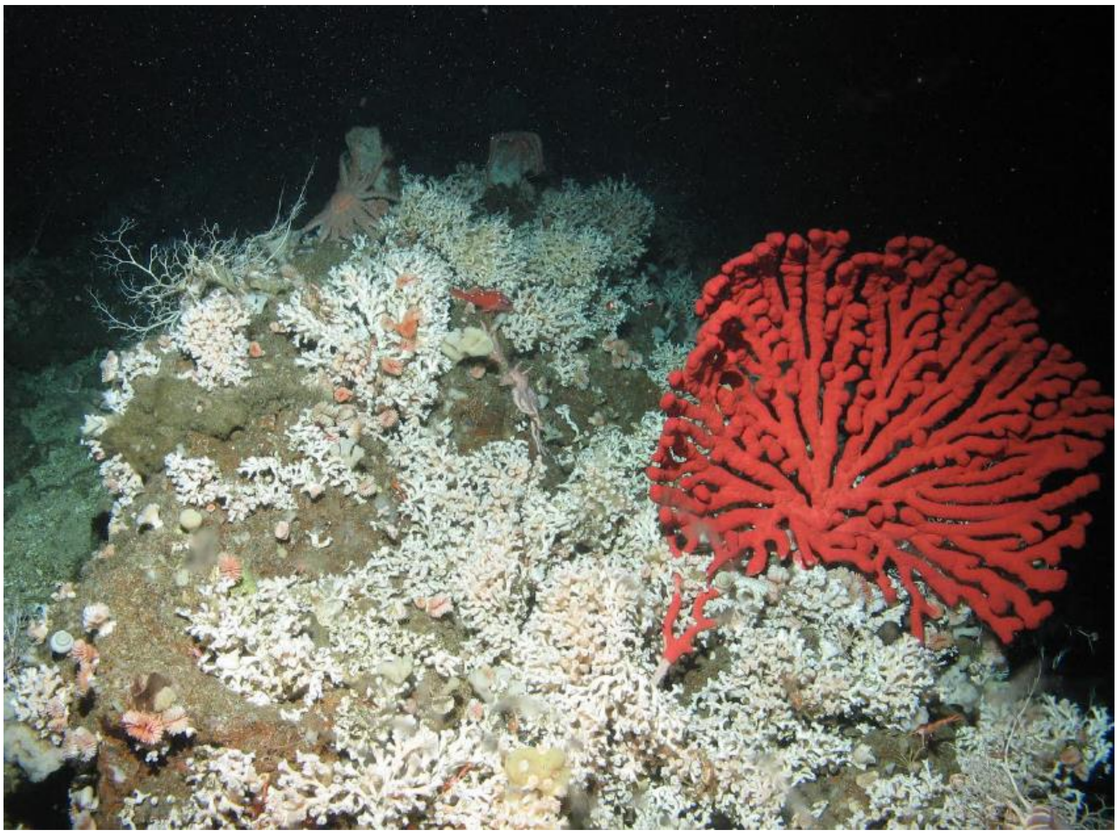

Figure 1-1: Deep-sea scleractinian coral with a bubblegum octocoral (in red) at 300 meters in depth, courtesy NOAA National Centers for Coastal Ocean Science (Hourigan et al., 2015).

But the environmental suitability of deep-sea coral is not well understood. Uniting deep-sea coral records with seafloor features will help researchers and ocean resource managers better understand deep-sea coral ecosystems, thus improving deep-sea coral conservation strategies. It is important to advance the understanding of deep-sea coral as they create intricate three-dimensional habitats, harbor commercially important fishes, and serve to reconstruct past climate and oceanic conditions (Hourigan et al. 2007).

1.1 Client

This project is intended for the National Oceanic and Atmospheric Administration's (NOAA) Deep Sea Coral Research and Technology Program. The mission of the Deep

Sea Coral Research and Technology Program is “to provide scientific information needed to conserve and manage deep-sea coral ecosystems” (NOAA, n.d.). To fulfill their mission, the Deep Sea Coral Research and Technology Program manages an online database containing georeferenced deep-sea coral records. Users can query the database and download its contents from a web application (Figure 1-2).

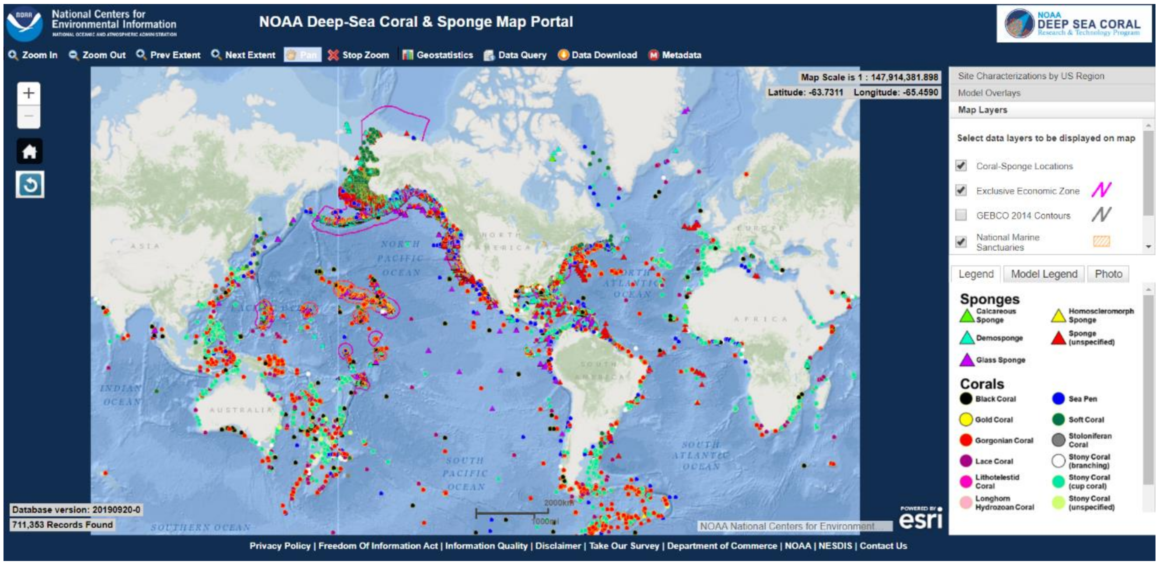

Figure 1-2: The NOAA Deep-Sea Coral & Sponge Map Portal

However, the deep-sea coral data lacks concurrent environmental information, information which may help scientists and resource managers conserve and manage deep-sea coral ecosystems.

1.2 Problem Statement

This project addressed the problem that NOAA’s deep-sea coral data lacked coincident environmental information such as topographic features. An absence of coincident topographic information hindered the ability to predict the locations of undiscovered deep-sea coral, thus, lowered the effectiveness of deep-sea coral habitat protection strategies.

Deep-sea coral ecosystems are under the threats of bottom trawling, seabed mining, hydrocarbon extraction, and ocean acidification (Roberts, Wheeler, & Freiwald, 2006). Yet the slow growth rate and weak post-disturbance recovery potential of deep-sea coral makes them particularly vulnerable to habitat disruption (Clark, 2006). Therefore, it is important to improve deep-sea coral conservation efforts by uniting deep-sea coral data with coincident geomorphology, a physical influence on their distribution.

1.3 Proposed Solution

NOAA’s deep-sea coral data was united to coincident geomorphology using a well-known geographic information system (GIS) operation, spatial join. Source geomorphic data came from the global seafloor geomorphic feature (GSGF) set created by Harris and others (2014). Attributes from these features were enriched onto the deep-sea coral data for the Deep Sea Coral Research and Technology Program to add to their online database, for researchers to use in deep-sea coral habitat models.

To further enhance deep-sea coral habitat modeling, slope position zones were classified for the Eastern U.S. EEZ (Figure 1-3). Attributes of coincident geomorphic features will help assess the habitat preferences of deep-sea coral species. This will improve deep-sea coral management strategies.

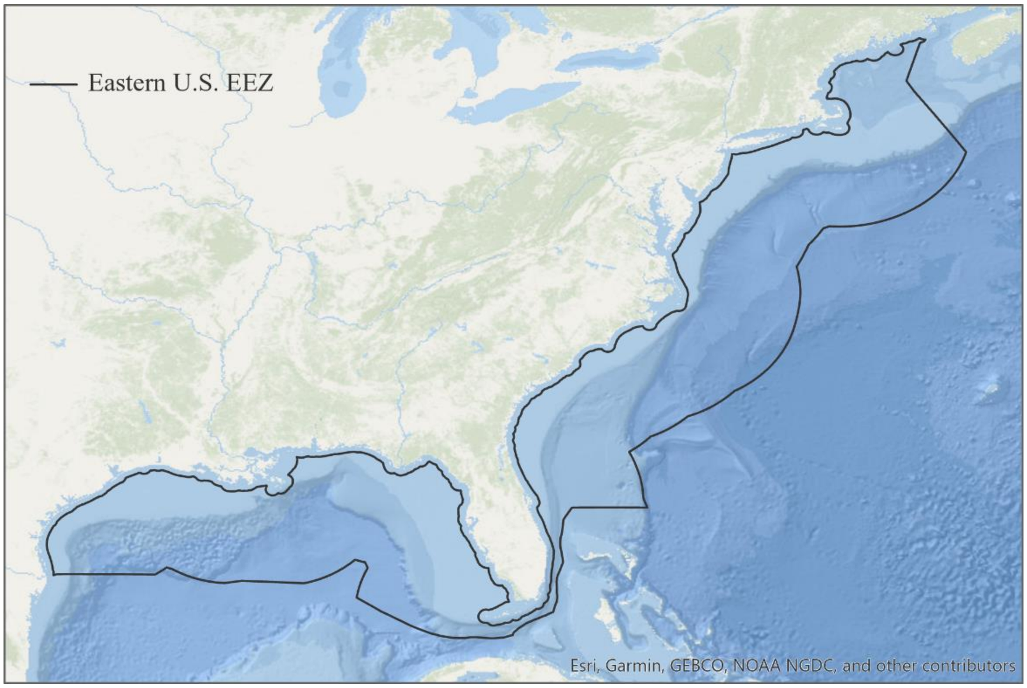

Figure 1-3: Eastern U.S. EEZ

1.3.1 Goals and Objectives

The principle goal of the project was to enrich NOAA's deep-sea coral data with coincident seafloor geomorphology. Meaning, every deep-sea coral record would contain information about the geomorphic feature on which it is located. The global seafloor geomorphic feature (GSGF) set created by Harris and others (2014) was used as the source geomorphic data. Because of GSGF's global coverage, same as the deep-sea coral data, its spectrum of features, 29 categories, and its accordance with International Hydrologic Organization standards of seafloor feature categorization, the physiographic feature set from Harris and others (2014) was fit to represent seafloor geomorphology. Associated attributes from this feature set can be included in NOAA's online database for ocean resource managers to use toward deep-sea coral habitat assessment.

The GSGF contains 24 data layers. Manually joining each layer to the deep-sea coral data requires substantial time since every GSGF layer must be processed before the join operation, and the join operation must be executed 24 times. Therefore, a second goal of the project was to spatially overlay the GSGFs to reduce the amount of time needed to join its attributes to the coral data.

A final goal of the project was to classify seafloor slope zones within the Eastern U.S. EEZ using a semi-automated process. Although the GSGF already represented benthic physiography, it was mostly developed manually and derived from 30-arc second resolution bathymetry. These methods may present issues since manually digitizing features is difficult to reproduce, and features elucidated from coarse resolution may omit details of smaller seafloor features that may be biologically important to deep-sea coral. Another inconvenience is that many of the features in this dataset overlap, making it difficult to use when analyzing the relationship between geomorphology and deep-sea coral. Using a semi-automated process of seafloor feature classification will allow researchers to (a) define seafloor features for the purpose of deep-sea coral conservation, (b) define features in a timely manner, (c) define features for specific regions, and (d) enhance the analysis of deep-sea coral habitat preferences.

1.3.2 Scope

The first project goal was to enrich NOAA's deep-sea coral records with an existing marine geomorphic feature set. A feature layer of the deep-sea coral records with coincident global seafloor geomorphic feature (GSGF) data was produced. Edits were made to the geomorphic features' schema to ensure that the enriching process was successful, and that the geomorphic data were efficiently stored; however, the spatial accuracy of the preliminary datasets was not manually corrected.

The final project goal, which required the greatest technical effort, was to create a slope zone feature layer from bathymetry data to enhance future analysis of the relationship between deep-sea coral and geomorphology for the purpose of deep-sea coral conservation.

1.3.3 Methods

To analyze coral and geomorphic feature relationships globally, deep-sea coral data was downloaded from NOAA's National Deep-Sea Corals and Sponges Database. Harris and others' (2014) global marine geomorphology features were obtained from www.bluehabitats.org. Data was added to a map in Esri's ArcGIS Pro and all field aliases with similar names were uniquely renamed. The Union spatial overlay tool and Spatial join tool were used to enrich the coral point features with coincident geomorphic feature attributes. The resulting data was imported into Excel and R to determine if any relationships existed between deep-sea coral and geomorphic features.

Then, the General Bathymetric Chart of the Ocean (GEBCO) 2019 global 15 arc-second bathymetry was downloaded from www.gebco.net for the purpose of classifying slope zones. Seafloor slope zones were then classified using topographic position, following the methods of Weiss (2001).

1.4 Audience

A reader of this report should understand the basic components and functions of GIS and its ability to perform geographic analysis and integrate spatial data from different origins. The target audience are the members of NOAA's Deep Sea Coral Research and Technology Program who are responsible for the online deep-sea coral database.

However, individuals concerned with the relationship between deep-sea coral and geomorphology or the classification of seafloor slope zones may enjoy and benefit from the following.

1.5 Report Organization

The structure and contents of the remainder of the report is as follows. The next chapter provides necessary information on the link between deep-sea coral and geomorphology and previous research concerning the classification of seafloor features. Chapter Three describes the plan, requirements, system design for the project. Chapter Four describes the design and contents of the geodatabase. Chapter Five details the methods used to unite deep-sea coral to geomorphology and classify seafloor features. Chapter Six describes the results of the analysis. Chapter Seven concludes the report and recommends GIS projects succeeding Uniting Deep-Sea Coral with Geomorphology

Chapter 2 – Background and Literature Review

This project aimed to connect deep-sea coral with geomorphology to help scientists develop more effective conservation strategies. Therefore, it was essential to develop an understanding of deep-sea coral and seafloor classification methods. Section 2.1 prefaces deep-sea coral habitat constraints. Section 2.1.1 explains why deep-sea coral is valuable while Section 2.1.2 explains their current threats. Section 2.1.3 describes the current knowledge of deep-sea coral distributions with respect to geomorphic features. Section 2.2 describes approaches to classifying seafloor features.

2.1 Deep-Sea Coral

Coral reefs are typically associated with shallow tropical seas. Yet 95 percent of the 361 million km^2 of ocean is 130 m below sea level (Clark, 2006). Deep-sea coral, also referred to as cold-water coral, live in temperatures ranging from 4 - 13˚ C and depths ranging from 39 – 3,000 m (Hourigan et al., 2007). However, other studies have observed coral at greater depths; Keller (1976) recorded a stony coral at 6,338 m (as cited in Freiwald et al., 2004). Yet the depth of the aragonite saturation horizon, the threshold where carbonate minerals dissolve – minerals which coral use for its skeleton – is an environmental limitation to the depth of coral growth (Guinotte, Buddemeier, & Kleypas, 2003; Roberts et al., 2006).

Unlike most shallow-water coral, deep-sea coral is azooxanthellate: they lack the symbiotic algae zooxanthellate, which provides shallow-water coral photosynthetically produced nutrients (Roberts et al., 2006). Although little is known about their nutrition and food source, deep-sea coral likely eats zooplankton and resuspended detritus, which coral captures with its polyps (Hourigan et al., 2007). Surface primary production followed by food transport to the sea floor and internal tidal waves likely supply deep-sea coral with food (Roberts et al., 2006).

2.1.1 Importance of Deep-Sea Coral

Deep-sea coral is valuable for biodiversity as they create habitats for fish (Stone, 2006) and invertebrate species (Edinger et al., 2011). For example, over 1,300 species were reported living on deep-sea reefs in the North East Atlantic (Roberts et al., 2006). In addition, commercially important species such as sea bass, shrimp, and crab have been associated with deep-sea coral (Hourigan et al., 2007). The vertical and horizontal structures of deep-sea coral provide species a place for (a) feeding, (b) spawning and nursing, (c) predator avoidance, and (d) substrate for sedentary organisms (Hourigan et al., 2007).

Deep-sea coral is also valuable for reconstructing past climate and oceanographic conditions (Heikoop et al., 2002). Radiometric dating off North West Africa indicate steady deep-sea coral growth rates over the past 50,000 years (Roberts et al., 2006). And the variations of annual coral skeletal band growth can be used as a proxy for the environmental conditions in which they grew (Risk, Heikoop, Snow, & Beukens, 2002). Paleoclimate information stored in coral can be used to determine the influence of climate change on fish populations (Heikoop et al., 2002) and to infer changes in thermohaline circulation, also known as deep-sea circulation, which is tightly coupled with global climate (Roberts et al., 2006).

2.1.2 Deep-Sea Coral Threats

While deep-sea coral has ecologic and economic value, it is vulnerable to anthropogenic disturbance markedly so because of their slow growth rates (Risk et al., 2002). Threats to deep-sea coral include (a) bottom trawling and other benthos destroying fishing practices, (b) oil and gas resource extraction, (c) fiber optic cable placement, and (d) ocean acidification (Hourigan et al. 2007). Brief details on the impact of bottom trawling and ocean acidification, the two greatest threats to coral, are given below.

The National Research Council (NRC, 2002) states that bottom trawling removes or destroys the physical seafloor constituents on which sessile coral inhabit. Damage from bottom trawling is noticeable worldwide (Hall-Spencer, Allain, & Fosså, 2002). Hundreds or thousands of years are needed for coral to recover from bottom trawling disturbance (Roberts et al., 2006).

However, Roberts and others (2006) believe the most insidious danger to deep-sea coral is ocean acidification. Most carbon dioxide released in the atmosphere is absorbed by the ocean, increasing the acidity of the ocean when it dissolves, and reducing the calcification rates of coral (Caldeira & Wickett, 2003; Kleypas, Buddemeier, Archer, Gattuso, Langdon, & Opdyke, 1999). Although the greatest increase in acidity occurs near the surface, sensitive deep-sea coral may also be at risk (Caldeira & Wickett, 2003). Furthermore, studies predict that acidification will raise the aragonite saturation horizon, thus reducing the habitat range of coral (Roberts et al., 2006). Improved deep-sea coral ecosystem management strategies should be developed to protect them from anthropogenic threats.

2.1.3 Deep-Sea Coral Distribution

Deep-sea coral has a global distribution (Figure 2.1). Yet their entire distribution is unknown because not all deep-sea areas have been explored. Additionally, survey efforts vary per geographic region. However, patterns emerge if we consider their range of physical habitats.

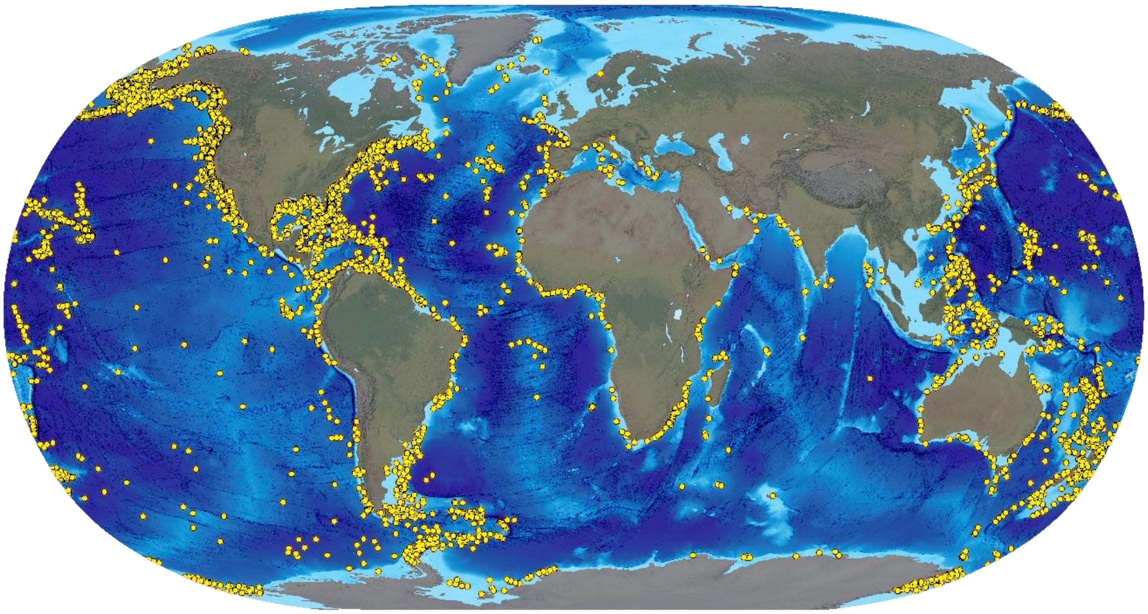

Figure 2-1: Global distribution of deep-sea coral.

The distribution of deep-sea coral is governed by major currents and their interaction with geomorphic features (Hourigan et al., 2007). Most coral species reside on hard substratum as they are sessile and must be fixed to the seabed (Guinotte & Davies, 2014). While currents erode sediments, exposing hard substrate, currents also carry suspended food to coral. Seamounts, canyons, pinnacles, and ridges provide these suitable conditions; many deep-sea coral species have been associated with them (Clark, 2006; Hourigan et al., 2007). Topographic relief is a commonality between these seafloor features. As such, previous studies have found slope to be an important variable for predicting deep-sea coral locations (Guinotte & Davies, 2014).

Along the boundary between the continental shelf and slope of Atlantic Canada, Edinger and others (2011) concluded that most deep-sea coral was associated with glacial features such as glacial tills, shelf-crossing glacial troughs, trough-mouth fans, and canyons. Within the glacial till, coral was colonized on boulders and cobbles. Areas with strong bottom currents and hard substrate contained the greatest concentration of coral. However, fine-grained unconsolidated sediments were a suitable habitat for sea pens and two species of gorgonian coral, *Acanella arbuscula*, and *Radicipes gracilis,* which have root-like appendages that anchor in sediment (Edinger et al., 2011).

Mortensen and Buhl-Mortensen (2005) studied coral distributions in the Gully, the largest submarine canyon in Atlantic Canada, and determined that deep-sea coral inhabited most parts of the canyon except for shallower regions. A study conducted in French Atlantic concluded that submarine canyons are a suitable habitat for deep-sea coral due to food availability, strong bottom currents, and the presence of hard substratum (Mol et al., 2010). Seamounts, like canyons, provide similar conditions which support coral growth (Clark, 2006). Seafloor geomorphology drives many physical and biological processes; so they can aptly model species distribution (Macmillan-Lawler & Harris, 2016).

2.2 Seafloor Classification Approaches

Digital elevation models (DEM) have been used to solve a variety of terrain problems such as plotting contour lines and studying surface changes (Miller & Laflamme, 1958), and delineating features of drainage basins (Flewelling, 1983). The seafloor can also be represented as an elevation model. Seafloor depth values are obtained from a variety of remotely sensed sources such as multibeam echo-sounders and satellite-derived gravity predictions which can then be converted into DEM data format to be used to delineate seafloor structures. Most seafloor classification studies also incorporate video, photographs, or other types of pseudo-ground truthed information in their interpretation (Lundblad et al., 2006).

Previous studies have catalogued ecologically important features such as seamounts (Morato et al., 2008; Yesson, Clark, Taylor, & Rogers, 2011) and submarine canyons (Harris & Whiteway, 2011) with hydrologic flow and sink algorithms.

Harris and others (2014) mapped four base features and eighteen discrete features, such as seamounts, ridges, and escarpments, globally (See Appendix A, B, & C for a description of all features). Manual digitization and a variety of automated techniques were used to delineate features from 30 arc-second bathymetry (Harris et al., 2014).

Used to study watershed metrics, Wiess (2001) developed a landform classification scheme by analyzing elevation values of a DEM. In his algorithm, each grid cell was assigned a topographic position value signifying its relative height in the landscape. Topographic position values were then categorized into discrete landform classes such as canyons, ridges, open slopes, and plains by incorporating other terrain metrics in the classification scheme. By combing topographic position values derived at multiple scales nested landforms were also identified such as local ridges within a broader plain. However, his technique has been used to model species distributions (Guisan, Weiss, & Weiss, 1999), and has been adapted to classify seafloor structures (Eredey-Heydorn, 2008; Iampietro, Kvitek, & Morris, 2005; Tagil & Jenness, 2008). In fact, his algorithms are so well used that they have been incorporated into a user-friendly interface built on the popular ArcGIS platform (Waldbridge et al., 2018).

2.3 Summary

This chapter answered the question *why should deep-sea coral be conserved?* Deep-sea coral provides economic and ecologic values. This chapter also outlined the urgency to understand deep-sea habitat preferences, their global distribution, and methods to classify seafloor geomorphic features; a strong influence on deep-sea coral distribution (Clark, 2006). This knowledge was assimilated in the system design of the project.

Chapter 3 – Systems Analysis and Design

A proper GIS solution was needed to address the need of NOAA's Deep Sea Coral Research and Technology Program to unite deep-sea coral with geomorphology. So, a system was designed to implement such a solution. Section 3.1 recapitulates the problem to be solved. Section 3.2 describes requirements needed to solve the problem. Section 3.3 describes the information products delivered to the Deep Sea Research and Technology Program to solve their problem. Lastly, Section 3.4 reviews the project plan and how it evolved throughout the project.

3.1 Problem Statement

NOAA's deep-sea coral data lacks information about the geomorphic feature on which deep-sea coral is located, an important environmental factor that influences their distribution (Clark et al., 2006). A deficiency of coincident physical information hinders the ability of ocean resource managers to devise effective deep-sea coral management strategies. NOAA's Deep Sea Research and Technology Program needed (a) an efficient way to enrich deep-sea coral data with attributes from the global seafloor geomorphic features (GSGF) and (b) a reproducible approach to classify seafloor geologic structures for the purpose of investigating deep-sea coral habitat suitability.

3.2 Requirements Analysis

Functional requirements describe the necessary behavior of a product. Nonfunctional requirements describe its attributes such as compatibility and usability. Both categories of requirements had to be explicitly established for the system to be designed to fit the needs of the client. Accumulating refined requirements occurred through interviews with the client and through observations made during the development process. Requirements for data, software, and enriching deep-sea coral data with coincident geomorphic feature data were collected prior to building the system.

3.2.1 Data Requirements

Three data sources were required: deep-sea coral, seafloor geomorphology, and bathymetry. Deep-sea coral data must be represented as points, contain a unique identifier field, and a field containing the taxonomic group of each coral. Seafloor geomorphology data must be represented as polygons, had global coverage, contained a field with the geomorphic name of each feature, and had a licensing agreement allowing its derivatives to be accessible to the public. Bathymetry data must be represented as a grid, have a spatial resolution finer than 30 arc-seconds, and geographically overlap a portion of the deep-sea coral data.

3.2.2 Software Requirements

NOAA's Deep Sea Coral Research and Technology Program uses ESRI ArcGIS Pro software. As such, deliverables had to be compatible with ArcGIS Pro software.

3.2.3 Coral Enrichment Requirements

Requirements for enriching deep-sea coral data with geomorphic feature data were documented in written form (Table 1).

Table 1. Coral Enrichment Requirements

Requirement Description
Enriched attributes derived from the global seafloor geomorphic feature (GSGF) set created by Harris et al. (2014)
Enrichment based on an intersecting spatial relationship
No coral data loss
Instruction manual explaining how to repeat the enrichment process

Enriched attributes had to be derived from the global seafloor geomorphic feature (GSGF) set created by Harris and others (2014). There were several reasons why the GSGF represented seafloor geomorphic structures: (a) its worldwide coverage matched the deep-sea coral database, (b) its feature categories were in accordance with International Hydrologic Organization standards, and (c) its Creative Commons License allowed it to be redistributed and modified in any medium or format. It was necessary for the GSGF data to be sharable since its attributes will be available within the client's online database for the public to download.

Enriched attributes from the GSGF polygons needed an intersecting spatial relationship with target coral points. An intersecting spatial relationship ensures that the enriched data represents environmental information that co-occurs with the deep-sea coral. Furthermore, an intersecting spatial relationship guarded against incomplete data enrichment of coral points that were on the boundary of a GSGF polygon, since target points that were on a boundary were still considered within the polygon.

The enriching process was not to result in deep-sea coral data loss. Every input coral point was present at the end of enrichment, even if it did not spatially intersect a GSGF polygon. If this was the case, the geomorphic attribute of the deep-sea coral point contained a null value.

The last requirement of coral enrichment was to write a step-by-step instruction manual explaining how to repeat the enrichment process. Written directions are required since the Deep Sea Coral Research and Technology Program will repeat the enrichment process when they obtain more deep-sea coral data.

3.3 System Design

The system design was based on the goal of enriching deep-sea coral points with geomorphic feature attributes and classifying seafloor features from bathymetry. The first deliverable was a point feature layer of NOAA's current deep-sea coral records enriched with coincident attributes from the global seafloor geomorphic features (GSGFs). This product contained the original deep-sea coral point layer unique identifier field and a field representing the GSGF which coincided with each coral.

The GSGFs was also delivered as a single polygon feature class. It contained a field representing the presence or absence of each geomorphic feature per coral. The geomorphic data can be joined to the deep-sea coral data by a key attribute so it can be added to the client's online database for scientists to develop more effective management strategies. Furthermore, the Deep Sea Coral Research and Technology Program can use this polygon feature to enrich future coral records they obtain.

The Deep Sea Research and Technology Program will also be delivered a polygon feature class of seafloor slope zones within the Eastern U.S. Exclusive Economic Zone (EEZ). These seafloor slope zones can be used by the client to further investigate deep-sea coral habitat preferences, and the methods used to classify the zones can be reproduced for other areas of deep-sea coral research.

3.4 Project Plan

A plan was developed at the start of the project to measure progress, allocate resources, and subdivide large tasks. It was divided into four stages: planning, design, development, and deploy. The original work breakdown schedule is shown in Table 2. Major tasks included coral data enrichment and classifying seafloor features.

Table 2. Original Work Breakdown Schedule

	Phase / Task Description	Start Date	End Date	Duration (hours)
1	Plan			
1.1	Research Client	30-Jan	30-Jan	2
1.2	Set Scope	31-Jan	5-Feb	4
1.3	Review Literature	10-Feb	1-Apr	100
1.4	Asses Risk	2-Apr	4-Apr	4
1.5	Plan Schedule	5-Apr	8-Apr	4
2	Design			
2.1	Download Data and Toolset	8-Apr	8-Apr	2
2.2	Enrich Coral Data with Geomorphic Data	9-Apr	9-Apr	5
3	Develop			
3.1	Develop Coral Geoform Join Tool	10-Apr	4-May	60
3.2	Analyze Coral Distribution per Seafloor Feature	5-May	12-May	20
3.3	Interpret and Summarize 3.2	13-May	27-May	48
3.4	Develop Atlantic Seafloor Classification	28-May	11-Jun	90
3.5	Develop Gulf Seafloor Classification	12-Jun	26-Jun	90
3.6	Develop Pacific Coast Seafloor Classification	27-Jun	11-Aug	90
3.7	Develop Alaska Seafloor Classification	12-Aug	26-Aug	90
3.8	Develop Hawaii Seafloor Classification	27-Aug	12-Sep	90
3.9	Develop Puerto Rico Seafloor Classification	13-Sep	20-Sep	40
3.10	Error Analysis for Seafloor Classification	21-Sep	25-Sep	32
4	Deploy			
4.1	Join Corals to Project Classified Features	26-Sep	27-Sep	2
4.2	Analyze Coral Distribution Per Project Feature	28-Sep	11-Oct	20
4.3	Interpret and Summarize 4.2	12-Oct	24-Oct	48
4.4	Compare Results	25-Oct	31-Oct	20
4.5	Deliver Products	1-Nov	1-Nov	2
4.6	Write Conclusions	2-Nov	5-Dec	100

Initially, to enrich deep-sea coral data with attributes from the GSGFs, a Python tool was developed to automate the process of spatially joining all 24 GSGF layers to the coral points (Table 2). However, during the development stage, a much more efficient solution was found to solve the problem; the GSGFs were combined into a single feature class with a union overlay operation. The resulting feature was then spatially joined to the deep-sea coral points to enrich them with GSGF attributes. This process produced the same result as spatially joining all 24 GSGF layers to the deep-sea coral points separately. Unfortunately, resources were allocated toward development of the Python tool, a tool which was never used during implementation nor delivered to the client.

The second major task was to develop six seafloor classification systems for six U.S. regions: Atlantic, Gulf, Pacific, Hawaii, Alaska, and Puerto Rico. Too little time was planned for such an ambitious task. During the development stage, since we were already behind schedule, one seafloor classification scheme was developed for the Eastern U.S. Exclusive Economic Zone (EEZ). The original seafloor delineation task could not have been accomplished given the available resources; a more prudent and realistic plan should have been initially devised.

3.5 Summary

The system design which addressed the solution of enriching deep-sea coral with geomorphology was chronicled in this chapter. Requirements needed to solve the problem, deliverables to the Deep Sea Coral Research and Technology Program, and the project's schedule were reviewed. After the system was precisely defined, data collection, database design, and project implementation could begin.

Chapter 4 – Database Design

The goal of this project was to enrich deep-sea coral data with coincident attributes regarding the geologic structure of the seafloor for NOAA's Deep Sea Coral Research and Technology Program to host on their online database. Users of the database expect query and speeds to be quick, so database design was critical to the success of this project since it effected the performance and usability of the database management system.

A sensible database was designed to model deep-sea coral and geologic structures of the seafloor. Section 4.1 describes the conceptual data model while Section 4.2 describes the logical data model. Section 4.3 summarizes where the data came from and Section 4.4 describes how it was processed for the purpose of uniting deep-sea coral with geomorphology.

4.1 Conceptual Data Model

A conceptual model abstractly describes the entities of interest and their relationships. It is often used to communicate ideas and help pave a route from the system design to a solution. The relationships between deep-sea coral and geomorphic features were represented visually as a Unified Modeling Language (UML) class diagram (Figure 4-1).

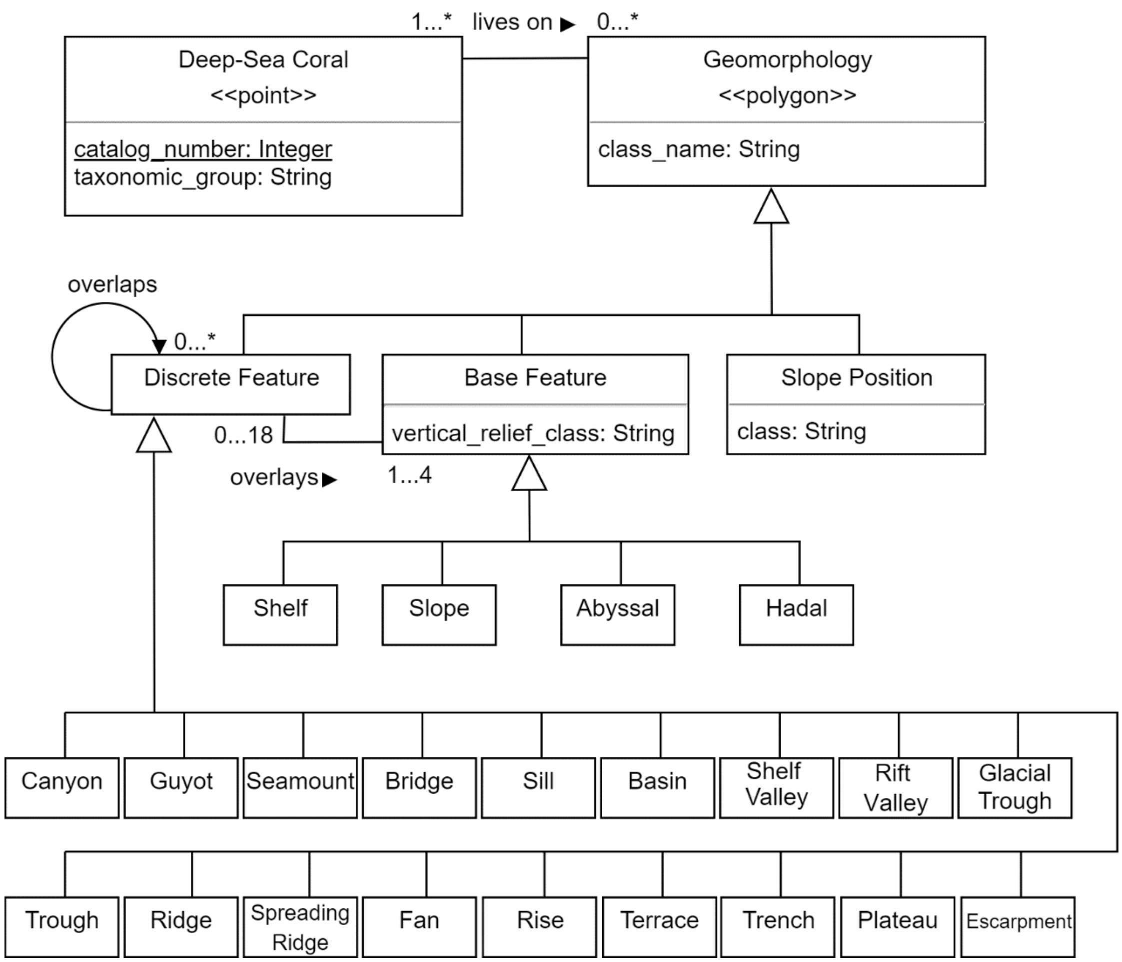

Figure 4-1: Conceptual Data Model

Deep-sea coral was represented as a point, and a single point was either a single organism or a garden of coral (Hourigan et al., 2015). However, the model for coral used in this project did not distinguish between these differences since the presence of coral signified suitable habitat. Deep-sea coral often lives on at least one geomorphic structure, although, many deep-sea corals can exist on more than one structure, not because the coral can relocate itself, but because each geologic structure can spatially overlap one another (Figure 4-1).

Three separate polygonal entities represented seafloor geomorphology: base features, discrete features, and slope position zones. Base and discrete features made up the global seafloor geomorphic feature (GSGF) set, which was defined by Harris and others (2014), experts in global seafloor geomorphology. Base features were four mutually exclusive expansive zones: shelf, slope, abyssal, and hadal. The shelf and abyssal zones were further subdivided into three vertical relief classes. Discrete features represented smaller features that overlay at least one broad zone. Discrete features, however, can also overlap other discrete feature types because of the natural transitions between geomorphic units and geologic processes (Federal Geographic Data Committee, 2012); for example, the perimeter of a seamount making up a larger ridge feature, or a submarine canyon hollowed within a shelf valley. Appendix A, B, and C describe the four base features, the six base feature vertical relief classes, and the 18 discrete features created by Harris and others (2014).

Slope position zones also represented seafloor geomorphic structures and contained four categories: depressions, crests, flats, and slopes. Slope position zones were derived from bathymetry data within the Eastern U.S. Exclusive Economic Zone (EEZ). Although a slope zone may be conceptualized as a subclass of a discrete feature or base feature, here they were kept as separate components of seafloor structure.

4.2 Logical Data Model

The logical data model moved the conceptual model closer to the physical world by describing the contents and organization of a database.

An ArcGIS File Geodatabase was used for data storage and management so that data could be smoothly communicated to the client. It housed the base and discrete feature classes of the GSGF set, deep-sea coral points, and data pertaining to the task of classifying seafloor slope zones in the Eastern U.S. EEZ such as bathymetry and its derivates.

Due to the large number of discrete geomorphic features and their overlapping nature of the GSGF dataset, a new feature was created representing all combinations of spatially overlapping discrete features (Figure 4-2). Although the attribute that defined each combined class did not conform to a normalized database structure since it contained multi-valued attributes, it was created to ensure that each coral would be counted only once for the purpose of analysis. Collapsing all 18 discrete features into one also increased database storage space and query speed. Furthermore, aggregating the 18 discrete geomorphic features into a single object hastens the process of enriching the deep-sea data with attributes from the geomorphic features, which was the purpose of housing geomorphic features in the database.

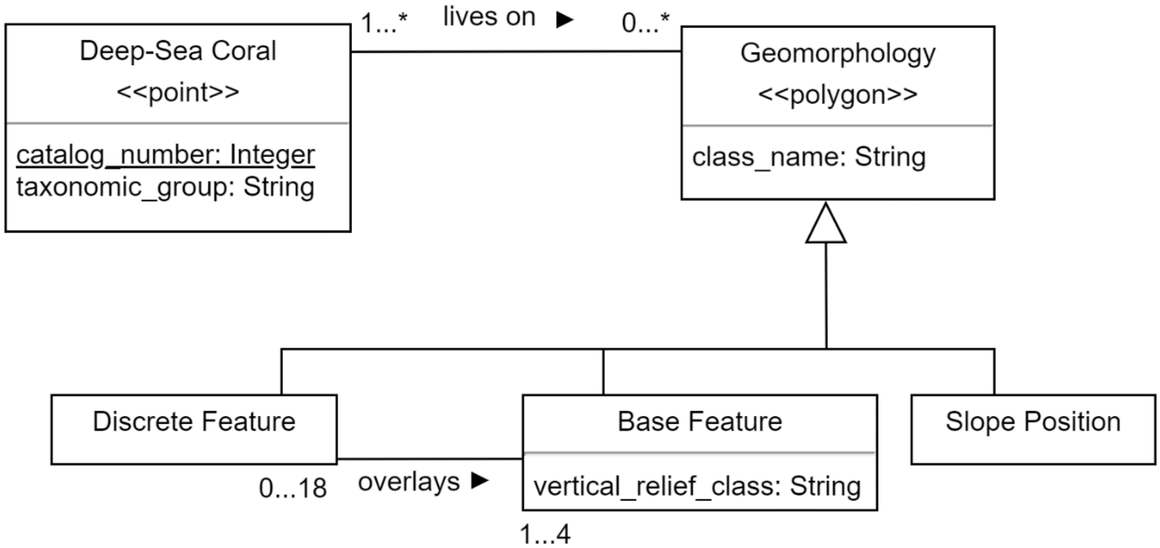

Figure 4-2: Logical Model

The four base features were similarly aggregated into one class (Figure 4-2). But since no base feature spatially overlapped one another the attribute of this new class, which represented the class of each base feature, contained single values.

4.3 Data Sources

Data used for this project are listed in Table 3. The principal data sources, deep-sea coral, seafloor geomorphology, and bathymetry, are described below.

Table 3. Data Sources

Data	Source	Format
Deep-Sea Coral Points	NOAA's National Database for Deep-Sea Coral & Sponges	CSV
Seafloor Geomorphic Polygons	Harris et al., (2014)	ESRI Shapefile
Seafloor Depth Grid	General Bathymetric Chart of the Oceans (GEBCO)	netCDF
U.S. EEZ Boundary Lines	NOAA's Office of Coast Survey	ESRI Shapefile

Deep-sea coral data came from NOAA's National Database for Deep-Sea Coral & Sponges. This database serves as an aggregation of georeferenced deep-sea coral and sponge observations. A variety of data providers contribute to the database and NOAA's Deep-Sea Coral Research and Technology Program performs quality control procedures before disseminating the collection. The database that is available to the public was downloaded in comma-separated values (CSV) format from the online map portal at https://deepseacoraldata.noaa.gov. Fields used for this project were Catalog Number, the unique identifier, and Vernacular Name Category, which represents the common name category of the coral or sponge (Hourigan et al., 2015).

Geomorphology data originated from the global seafloor geomorphic feature (GSGF) set created by Harris and others (2014) (Figure 4-2). This dataset included four base features and eighteen discrete features (see Section 4.2 for details). Base and discrete features were created manually and from a variety of automated techniques using 30 arc-second bathymetry. These features were downloaded in ESRI shapefile format at http://www.bluehabitats.org. Fields used for this project were Geomorphic, which represents the name of each geomorphic zone or feature, and Class, a subclass of the shelf and abyssal zones based on differences in vertical relief (Harris et al., 2014).

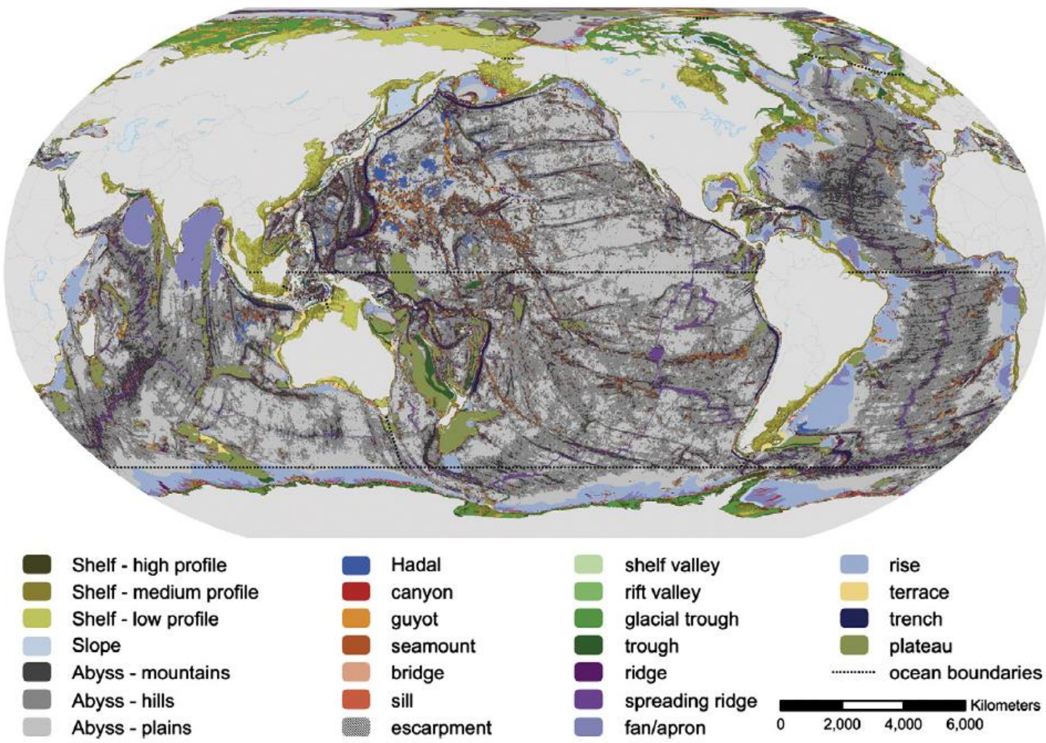

Figure 4-2: Global seafloor geomorphic feature (GSGF) set (Harris et al., 2014)

The General Bathymetric Chart of the Oceans' (GEBCO) 2019 Grid was used for seafloor depth data because it covered the entire study region, the Eastern U.S. EEZ. The GEBCO 2019 Grid is a continuous terrain model of ocean and land. It is composed of data from many sources; sources of depth values within the Eastern U.S. EEZ include Shuttle Radar Topography Mission (SRTM) 15+ satellite-derived gravity data, multibeam data, pre-generated values from a variety of source types, and soundings data from SRTM 15+ (Figure 4-3). Because the underlying data were collected by different methods, different geographic regions have varying quality (British Oceanographic Data Center, n.d). The global GEBCO 2019 Grid was downloaded in netCDF format at https://www.gebco.net.

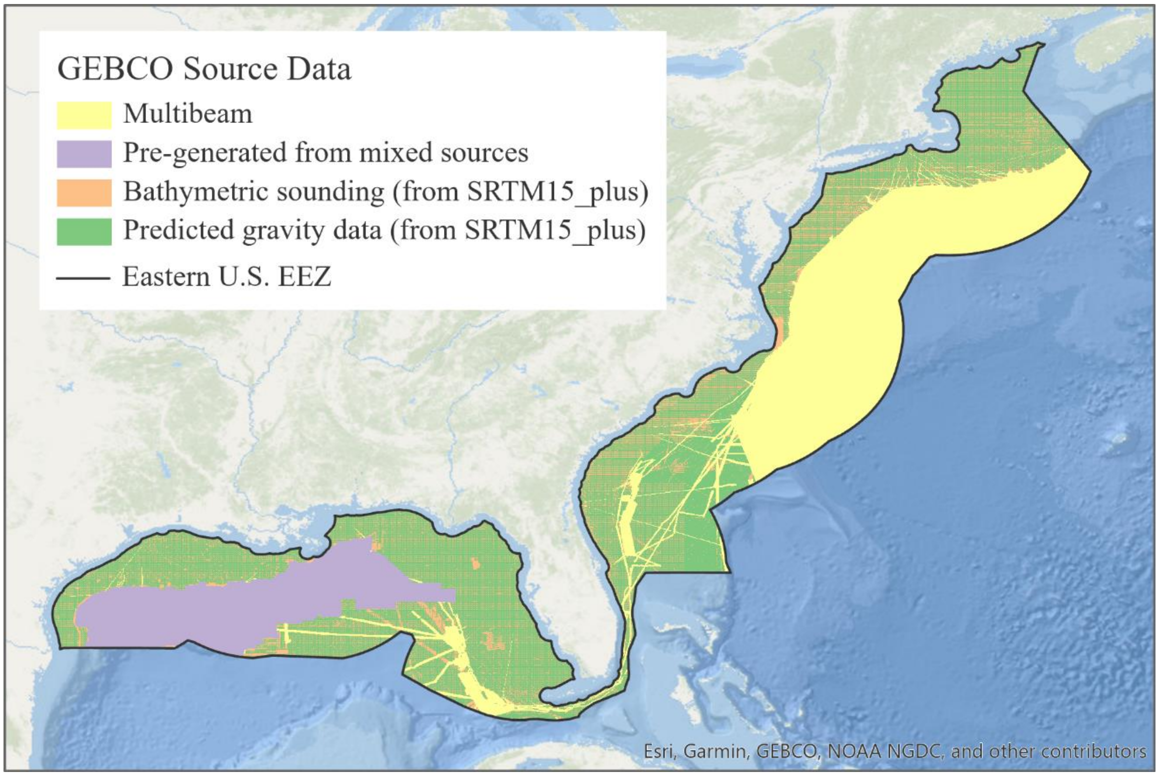

Figure 4-3: GEBCO's data sources for depth values

4.4 Data Preparation

Data used to unite deep-sea coral with geomorphology and to classify seafloor features had to be cleaned-up and prepared beforehand.

Deep-sea coral data were converted to a point feature class and irrelevant fields were removed. The Catalogue Number field, the unique identifier, was checked to ensure that all coral records had a unique ID, which they did.

Seafloor geomorphology shape files were converted to polygon feature classes and irrelevant fields were removed. All 24 features had a field named Geomorphic, which represented the name of each geomorphic zone or feature. The Geomorphic field of each feature was renamed to the name of the feature to ensure that there would be no ambiguity of the field's source after it was joined to the deep-sea coral points.

The GEBCO 19 bathymetry grid was converted to a raster and projected to the World Plate Carrée coordinate system for topographic analysis. World Plate Carrée was the projection of choice because the shape of its grid cells, perfect squares, match the shape of the raster cells. The bathymetry raster was then clipped to the Eastern U.S. EEZ boundary; however, the Eastern U.S. EEZ boundary polygon was first created by tracing the Atlantic and Gulf EEZ boundary lines. Then, to guarantee an accurate topographic analysis, all bathymetry cells with an empty value were replaced with the mean of its neighbors and a mean focal filter was passed over the raster to reduce data collection artifact and errors.

4.5 Summary

Database design decisions, data source choices, and data preparations were presented. Most notable is that seafloor geomorphology was modeled as nonoverlapping slope position zones, nonoverlapping base feature, and overlapping discrete features. This database design choice, along with the rest, had consequences on system implementation and analysis.

Chapter 5 – Implementation

To reiterate, the two goals of this project were to (a) enrich deep-sea coral data with attributes from the global seafloor geomorphic features (GSGFs) and (b) classify seafloor slope zones within the Eastern U.S. Exclusive Economic Zone (EEZ) for the purpose of elucidating relationships between deep-sea coral and geologic structures to aid in conservation measures.

The methods to meet these goals are documented in detail in this chapter. Section 5.1 describes how the GSGFs were joined to the deep-sea coral data while Section 5.2 describes the classification of slope zones within the Eastern U.S. EEZ.

5.1 Joining Coral to World Seafloor Geomorphology

GSGFs had their undesirable fields deleted and the Geomorphic fields' names were renamed to match the name of each respective feature. Then, the two components of the GSGFs, base features and discrete features, were joined to the deep-sea coral points and analyzed separately.

The four base features – shelf, slope, abyss, and hadal – were combined into one feature class with a union overlay operation. The fields representing the presence of each base feature were merged into one field and spatially joined to the coral based on an intersecting spatial relationship. None of the base features spatially overlapped each other.

Since the discrete features did spatially overlap each other, however, a union spatial overlay was performed, which included all 18 discrete features, to calculate the geometric overlaps and nonoverlaps between the discrete features. The layer resulting from the union overlay contained 18 fields, each representing presence or absence of each discrete feature. Feature presence was represented as the name of the feature while absence was represented by a blank string. A Python script was developed to concatenate the 18 fields into a new field which represented overlapping and nonoverlapping discrete features. The type of this new field was text and it contained the first three letters of each present discrete feature.

Next, a new text field was added to the unioned discrete features which acted as an identifier for each overlapping discrete feature combination. The text identifier contained 18 digits, one for each discrete feature class. The placeholder of each digit represented a discrete feature class. The value for each digit represented the presence or absence of each discrete feature as one or zero respectively; in essence, it was a binary value, which was then converted into a decimal value. Table 6 shows an example of the binary and decimal codes.

Table 4. Example of binary and decimal values for discrete features

Feature Name	Binary Value	Decimal Value
Bridge	000000000000000001	1
Trough	000000000000000010	2
Trench	000000000000000100	4
Bridge & Trough	000000000000000011	3
Bridge & Trench	000000000000000101	5
Trough & Trench	000000000000000110	6
Bridge & Trough & Trench	000000000000000111	7

Because the integer identifier was shorter than the text field, it improved the efficiency of the database. Furthermore, the integer identifier improved queries of discrete feature combinations because queries could more easily identify integers rather than text. The integer identifier of the unioned discrete feature was spatially joined to the deep-sea coral points and functioned as the foreign key to relate each discrete feature to a deep-sea coral.

Query execution speeds were tested in a simulation in which a user was searching for deep-sea coral points that intersected escarpments, fans, rises, seamounts, and ridges. Three groups were created (1) an attribute query of the decimal code representing the five unioned features, (2) an attribute query of five fields representing the five separate features, and (3) a spatial query in which discrete features were not spatially joined to the coral. Query execution time of the decimal code, the five attributes, and the spatial query took 0.27, 2.19, and 19.35 seconds respectively. These results agree with the notion that decimal codes are relatively fast to query. Based on the results, it is recommended that the decimal codes be implemented in the client’s online database so its users will experience quick response times.

5.2 Classifying Seafloor Slope Zones from Topographic Position

Although the deep-sea coral points were already enriched with data from the global seafloor geomorphic features (GSGFs), seafloor slope zones were classified for the Exclusive Economic Zone (EEZ) of the contiguous Eastern U.S. to further analyze the relationship between deep-sea coral and geomorphic structures.

After the GEBCO 19 seafloor depth grid was processed and clipped to the Eastern U.S. EEZ, it was used to derive topographic position index (TPI) and slope; both were used to classify seafloor slope zones. Topographic position categorizes landforms (i.e. hilltop, slope, and plain) based on elevation relative to the overall landscape (Weiss, 2001). TPI used in marine contexts has been labeled benthic position index (BPI); both involve the same underlying algorithm and will be referred to as TPI below.

TPI was calculated for each cell in the GEBCO 2019 digital elevation model (DEM) by comparing the elevation value of a cell to the mean elevation of surrounding cells in an annulus, a ring-shaped moving window composed of two concentric circles. The formula to calculate TPI was adapted from Weiss (2001) and is as follows:

tpi<*scalefactor*> =int((dem – focalmean(dem,annulus,*irad*,*orad*)) + 0.5)

where

scalefactor = outer radius in map units
irad = inner radius of the annulus in cells
orad = outer radius of the annulus in cells

This formula has been implemented for ArcGIS in the Benthic Terrain Modeler toolbox and TPI was computed using a tool within the toolbox (Walbridge et al., 2018). TPI was converted to an integer to reduce the storage size of the resulting raster. The 0.5 was added before integer conversion to ensure floating point values would be rounded up or down correctly. An annulus was used as the shape of the neighborhood to exclude adjacent cells when measuring the mean of a cell's surrounding depth values (Walbridge et al., 2018).

Positive TPI values indicated locations that were higher in elevation than the neighborhood average, such as a ridge. Negative TPI values indicated locations that were lower in elevation than the neighborhood average, such as a valley, while TPI values near zero indicated either flat regions or regions of constant slope (Figure 5-1).

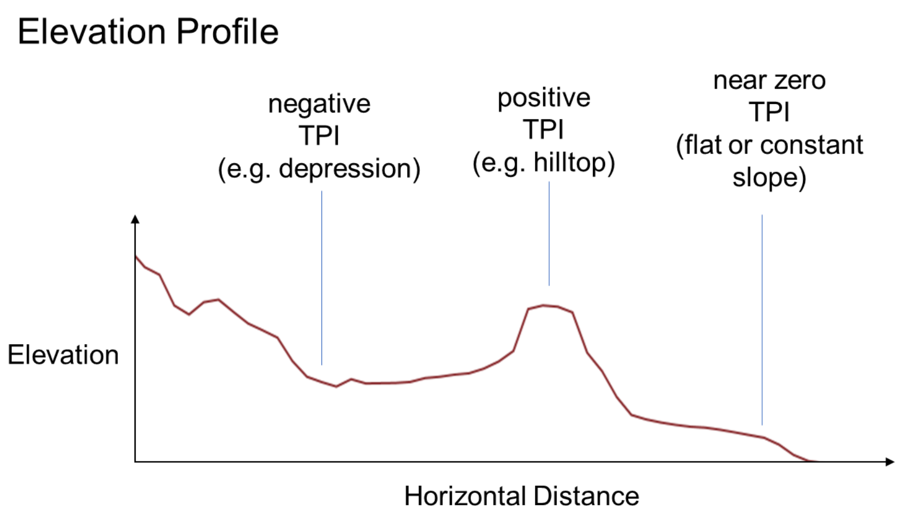

Figure 5-1: Description of TPI values

TPI was impacted by the edge effect, a phenomenon of raster neighborhood analysis, which alters cell values on the margin of the DEM where there is a lack of neighboring cells (Impietro et al., 2005). Therefore, a 10 cell, 4640 m, buffer was created inside the perimeter of the study region and all ensuing analysis was performed interior to the buffered region.

TPI is scale dependent, and the size of the outer radius will affect the final classification scheme. Large outer radius lengths elucidate broad geomorphic features, while shorter radii show smaller-scale features (Weiss, 2001). Choosing an appropriate neighborhood size was a trial and error process. In this study, five TPI grids were generated from outer annulus radii of 5, 10, 25, 50, and 100 cells using a 464 m DEM. Therefore, the neighborhood size, also known as the scale factor, for each grid was 2319, 4637, 11593, 23187, and 46374 m respectively. Figure 5-2 shows a section of the five TPI grids that were generated.

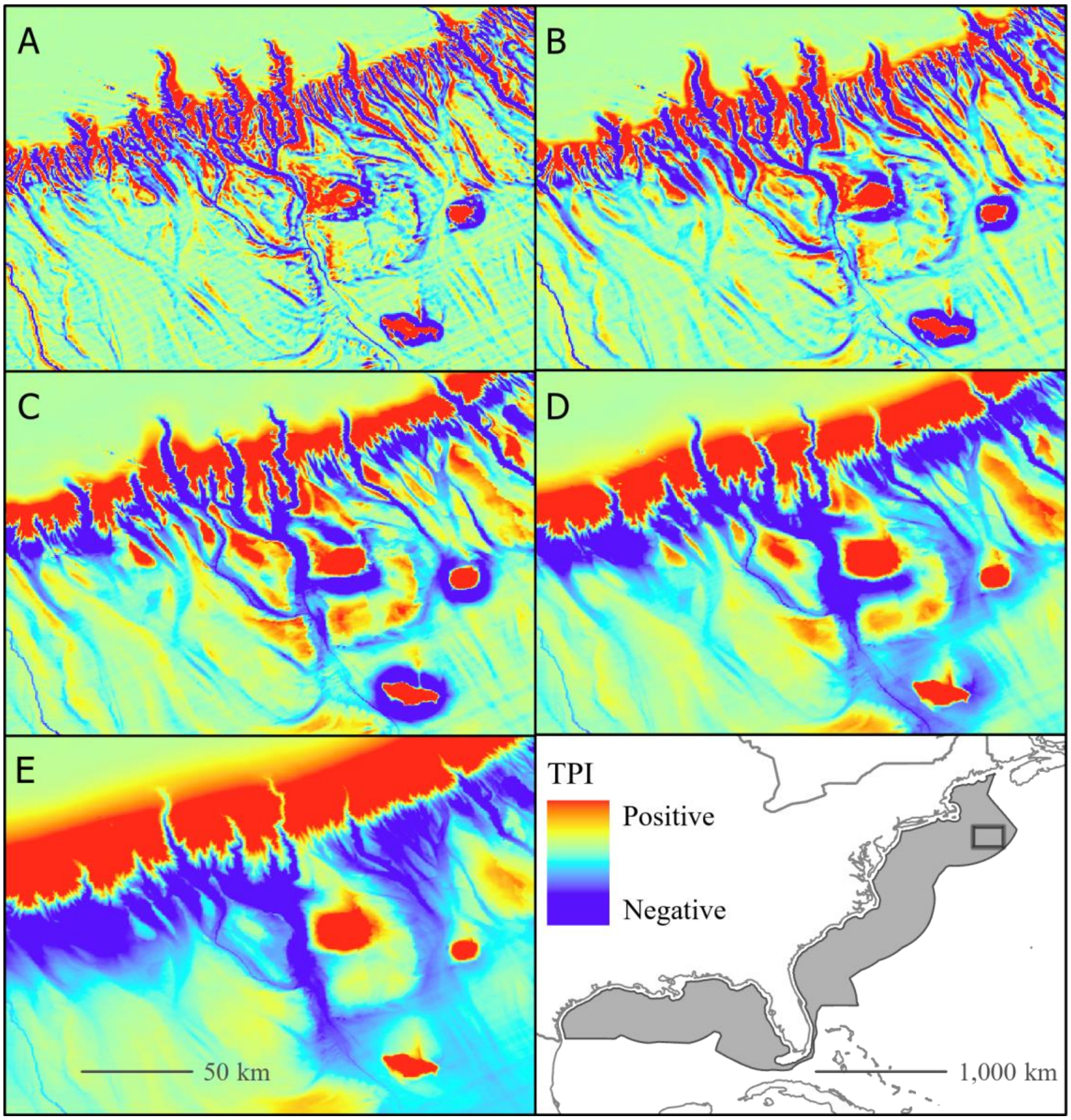

Figure 5-2: TPI grids calculated from different neighborhood sizes: (A) 2319 m, (B) 4637 m, (C) 11593 m, (D) 23187 m, and (E) 46374 m.

Then, based on the decision trees of Lundblad and others (2006), each TPI grid was portioned by standard deviation (SD) to classify four seafloor slope zones (Table 7). A standard deviation of 3.5 was chosen as the class breakpoint to emphasize sloping regions within the Western Atlantic canyon system which separated ridge crests from canyon depressions. Since both flat regions and regions of constant slope are represented by TPI values near zero, slope was used to separate these two classes. A Python script was developed using the Spatial Analysis package from the ArcPy module to perform the image classification. Figure 5-3 shows the slope zones that were classified for each TPI neighborhood size.

Table 5. Slope zone classification description

Seafloor Zones	Class Breaks
1 Depression	TPI < - 3.5 SD
2 Crest	TPI > + 3.5 SD
3 Flat	3.5 SD ≥ TPI ≥ - 3.5 SD and slope ≤ 5˚
4 Slope	3.5 SD ≥ TPI ≥ - 3.5 SD and slope > 5˚

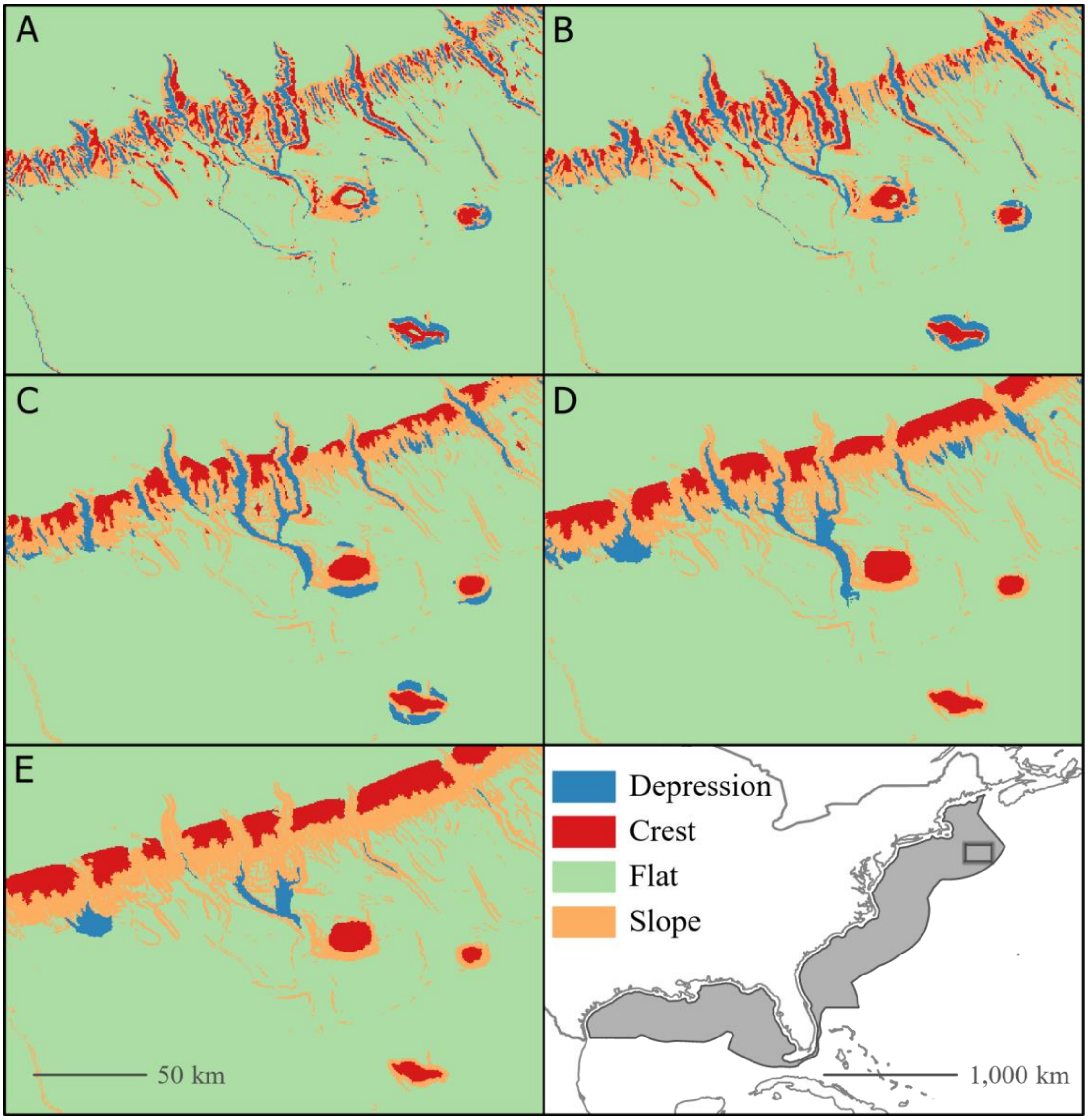

Figure 5-3: Slope zones classified from different TPI neighborhood sizes: (A) 2319 m, (B) 4637 m, (C) 11593 m, (D) 23187 m, and (E) 46374 m.

Each slope zone map was visually compared to a hillshade layer of the seafloor elevation surface, a greyscale image of illumination and shadow based on the sun's relative position. Furthermore, each slope zone map was visually compared to the seafloor terrain in an ArcGIS 3D Scene in which the original bathymetry raster was used to represent ground surface elevation. Both visual analyses were performed to evaluate the accuracy of each seafloor zone map. Inspection occurred at four separate locations along the continental margins of: Louisiana, West Florida, Virginia, and New England.

5.2.1 Post-Classification Smoothing

After slope zones were classified, the resulting raster contained small regions of seemingly incorrectly classified zones of a salt-and-pepper appearance; this occurred due to spectral variability when the classification was performed for each pixel (Lillesand & Kiefer, 1994 as cited in Giles, 1998). To eliminate such regions, post classification smoothing was performed by majority filter and by the removal of small homogeneous regions.

First, the Majority Filter tool was used to replace the value of a cell with the majority of its four contiguous neighbors. Then, zones less than 5,104 m^2, or 11 cells, in size were removed. This was done by first identifying regions smaller than 11 cells in size with the Region Group function which identified the number of cells per each region. Then, the Extract by Attribute tool was used to mask the homogeneous regions smaller than 11 cells, and the Nibble tool was run to replace cells within the mask with the values of its nearest neighbors (Erdey-Heydorn, 2008). The resulting smoothed raster was compared to the hillshade and 3D elevation surfaces to ensure that no significant detail was lost and to ensure that slope zones within the continental margin still reflected the terrain.

The raster of slope zones was converted to a polygon feature and the Smooth Polygon tool was used to remove the sharp edges which manifested from the raster cells.

5.3 Summary

Methods used to (a) enrich deep-sea coral data with GSGFs and (b) classify seafloor slope zones within the Eastern U.S. EEZ were detailed in this chapter. The 18 discrete GSGFs were combined into one feature class with a union spatial overlay and then spatially joined to the coral data for the purpose of enrichment. Then, four slope position zones were classified based on TPI within the Eastern U.S. EEZ and spatially joined to the coral data. These two tasks were performed to analyze associations between deep-sea coral and the underlying structure of the seafloor.

Chapter 6 – Results and Analysis

Results of enriching the Deep Sea Coral Research and Technology Program's deep-sea coral data with the Global Seafloor Geomorphic Features (GSGF) set's base features and discrete feature are summarized in sections 6.1 and 6.2. Attributes from the GSGF can be used in the Program's online database and used for deep-sea coral habitat research. Section 6.3 examines the slope position classification maps that were produced for the Eastern U.S. Exclusive Economic Zone (EEZ). Classification methods involving topographic position index (TPI) can be used by deep-sea coral habitat modelers for their study regions.

Deep-sea coral samples were not spatially independent of other each other due to sampling biases, and were restricted to presence-only data. Therefore, inferential testing of deep-sea coral and seafloor geomorphology was not conducted.

6.1 Base Features

Base features included the shelf, slope, abyssal, and hadal zones; their combined area represents the complete area of the seafloor. Yet, 512 coral points, 0.00007 % of the data, did not intersect a base feature. Not all coral records intersected a base feature because there was a gap between terrestrial land masses and the shelf, the shallowest base feature; some coral points were in that gap. Since the nearest base feature to all non-intersecting coral points was a shelf feature, and all non-intersecting coral points were in between a terrestrial land mass and a shelf feature, the seafloor feature adjacent to a continent or island (Harris et al., 2014), all non-intersecting coral points were categorized as on a shelf.

The highest percentage of deep-sea coral was located on the slope (48.7%), followed by the shelf (29.4%), and abyssal zone (21.9%), while less than 0.01% of the coral was in the hadal region. Coral density (# / 1,000 km^2) was also calculated for each base feature to account for area (Figure 6-1). Deep-sea coral exhibited the highest density on the slope, followed by the shelf, abyssal, and hadal zones (Figure 6-1).

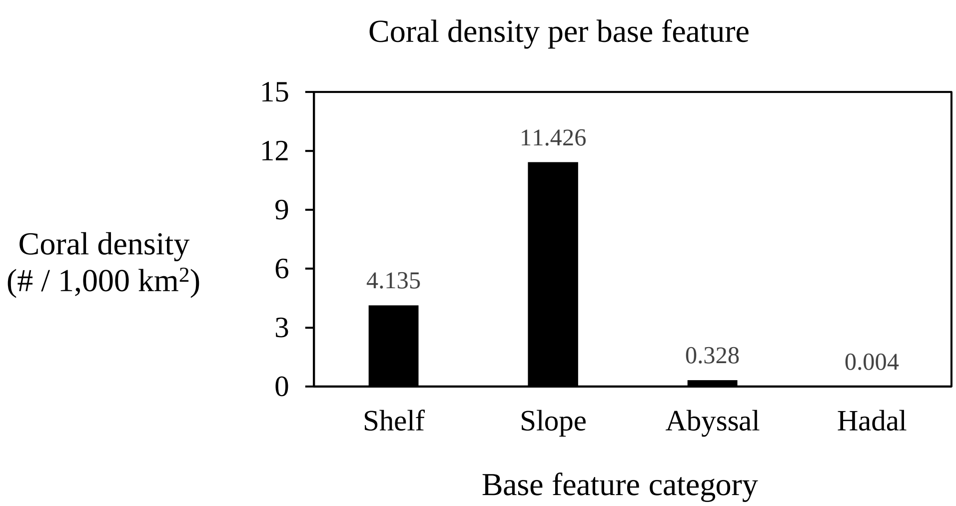

Figure 6-1: Deep-sea coral density per base feature category.

The GSGF set subdivided the shelf and abyssal features into three vertical relief classes. The highest vertical relief class for both base features showed the highest coral density (# / 10,000 km^2), while the lowest vertical relief classes showed the lowest coral density (Figure 6-2 and Figure 6-3).

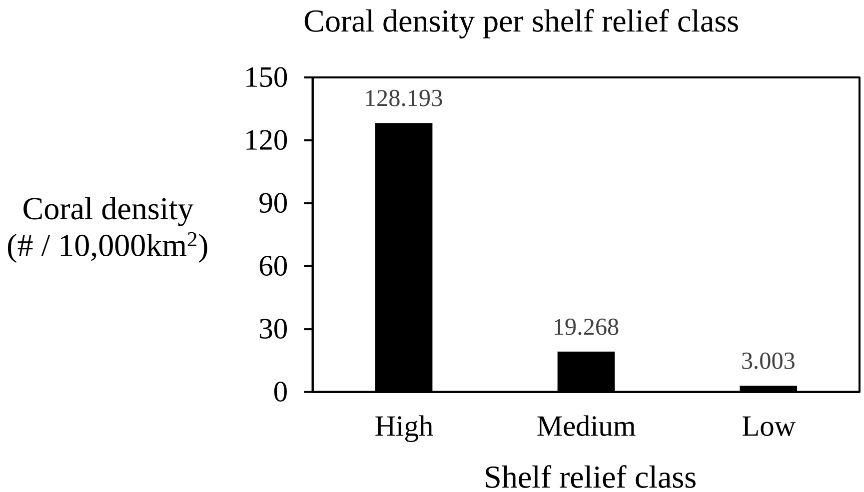

Figure 6-2: Deep-sea coral density per shelf relief class.

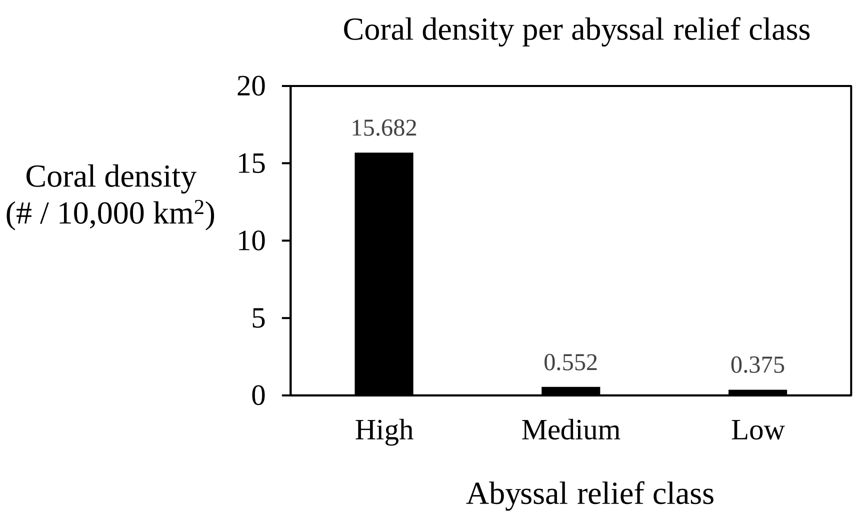

Figure 6-3: Deep-sea coral density per abyssal relief class.

Although coral density was highest in the slope base feature and in the highest vertical relief classes of the abyssal and shelf feature, due to biases inherent in the coral data, these results do not illustrate deep-sea coral's affinity for these features.

6.2 Discrete Features

There were 18 discrete feature categories in the GSGF set. These features, along with the base features, can be joined to the Deep Sea Coral Research and Technology Program's online database for the public to use. The union spatial overlay operation that was performed to determine spatial overlaps between the 18 discrete features resulted in 690 discrete feature combinations. Deep-sea coral was located in 130 of the 690 discrete feature categories. While this was may seem to be many discrete feature classes, the total possible number of discrete feature combinations was 262,144. 60.2% of the coral data did not intersect a discrete feature because, unlike base features, discrete features did not cover the entire ocean area.

Discrete features with the highest coral density included escarpments, canyons, fans, guyot, ridges, rises, seamounts, and terraces (Figure 6-4).

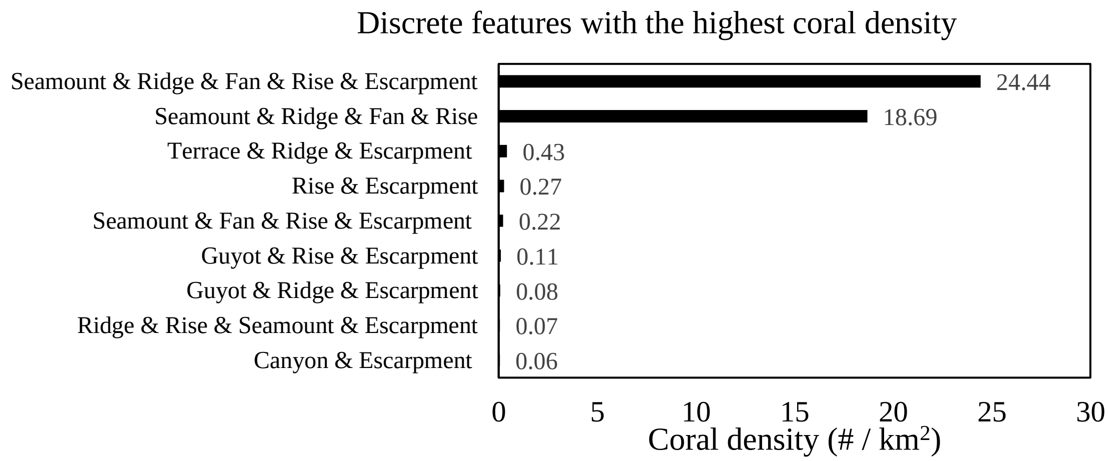

Figure 6-4: Discrete features with the highest coral density (# / km^2).

The discrete features with the highest and second highest coral density contained the same combination of feature classes but one was not overlain by an escarpment (Figure 6-4). These features occurred in only two locations globally, off the Alaskan Panhandle and Monterey, CA; both features were a part of known seamounts (Figure 6-6). Maximum coral density per discrete feature was also recorded (Figure 6-5). The Davidson Seamount off Monterey contained the highest maximum deep-sea coral density, a place of extensive oceanographic research. The disproportionate number of benthic surveys in Monterey skewed observed deep-sea coral density. Overcoming this spatial bias would require removing coral samples in a logical fashion, such as eliminating adjacent samples, and using a presence-only model, techniques used in a predictive deep-sea coral habitat suitability study (Guinotte & Davies, 2014).

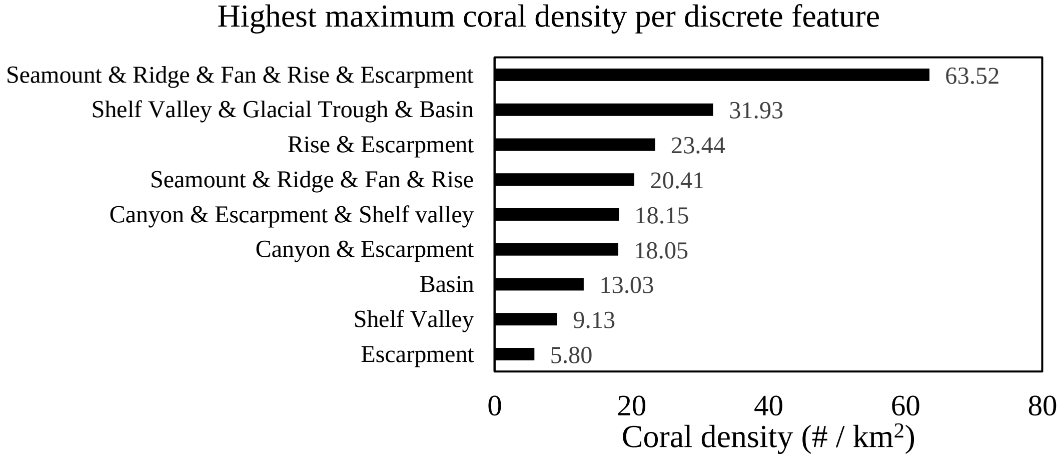

Figure 6-5: Highest maximum coral density per discrete feature.

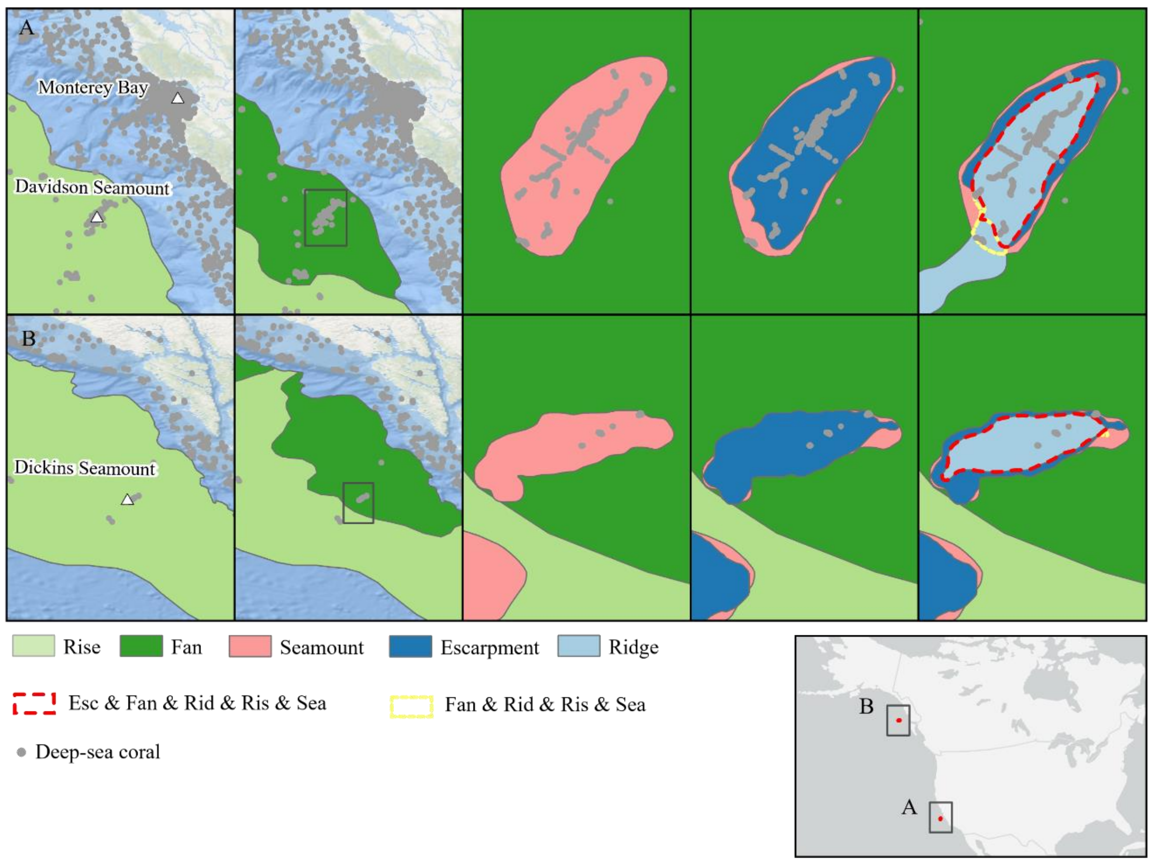

Figure 6-6: Overlapping discrete features which have the highest coral density.

Although coral density was influenced by an uneven sampling distribution, seamounts which overlap other features may suggest that locations with similar feature combinations are suitable for deep-sea coral. Seamounts are known to be hotspots for coral fauna since they are composed of hard rock, which many deep-sea coral species reside on, and direct current flow, which carry suspended nutrients to the immobile coral

(Clark, 2006). Two similar seamount features exist which also had high coral density: seamount overlain with fan, rise, and escarpment, and seamount overlain with ridge, rise, and escarpment (Figure 6-4). Deep-sea coral has yet to be discovered on some of these features, but their complex geomorphic qualities may constitute potential habitats for deep-sea coral and good candidate locations for future expeditions and marine protected areas (Figure 6-5).

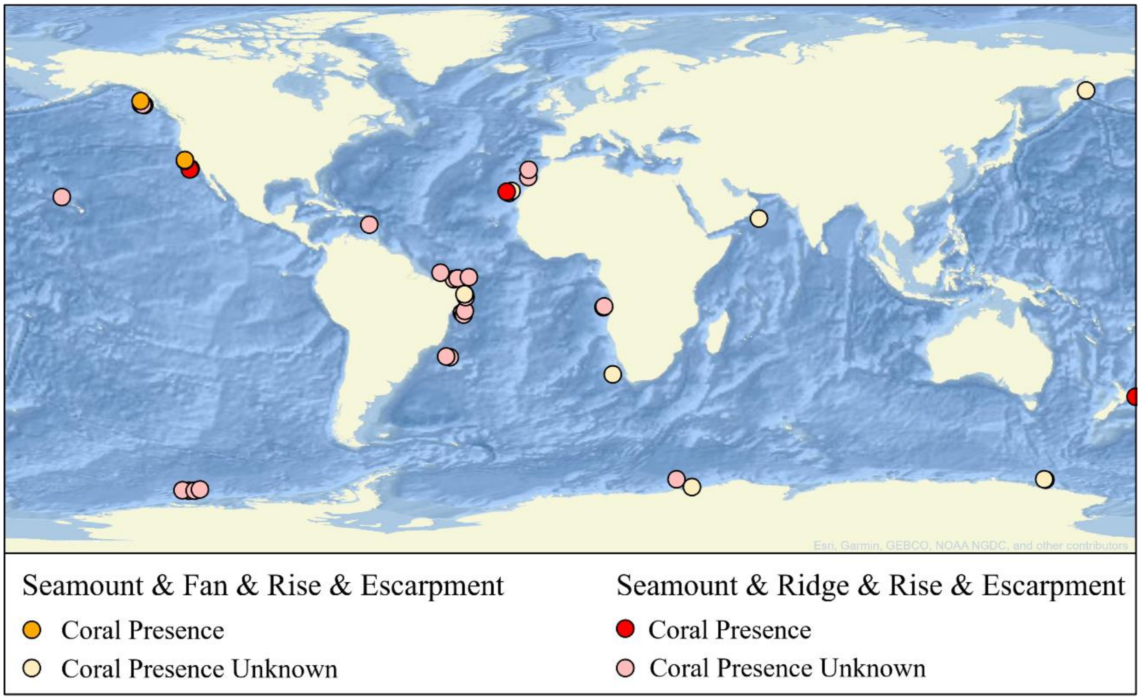

Figure 6-5: Seamounts that may support deep-sea coral.

6.3 Slope Position zones in the Eastern U.S. EEZ

Five slope position zone maps were created for the Eastern U.S. EEZ from TPI calculated from various neighborhood sizes; each map contained four slope position categories: crests, depressions, flats, and slopes. The five maps illustrated how neighborhood size influenced the classification of slope position zones; smaller neighborhoods more accurately elucidated smaller slope zones (Figure 5-3).

Across all five maps, flats were the category covering the largest area with percentages ranging from 95.25% to 96.08% (Table 8). The Western Atlantic is along a passive continental margin where tectonic activity, which gives rise to topography, is minimal. Compared to an active continental margin, the passive continental shelf of the Western Atlantic is wider and the transition between the continent and the abyssal plain is much more gradual (Harris et al., 2014).

Table 6. Percentage of slope position zones based on TPI for different neighborhood sizes.

Slope Zone (%)	Neighborhood Size (m)				
	2,319	4,637	11,593	23,187	46,374
Flat	96.08	95.95	95.60	95.25	95.25
Slope	2.26	2.42	2.59	2.76	3.03
Depression	0.90	0.92	1.06	1.11	0.92
Crest	0.76	0.71	0.75	0.88	0.79

The category crest coincided with canyon rims, seamount tops, the ridge of the Florida Escarpment, and the rims of basins in the Gulf of Mexico (Appendix D). The category depression corresponded to canyon bottoms, seamount bases, the base of the Florida Escarpment, and the basins in the Gulf of Mexico (Appendix D). Bases of extruding features were classified as depressions since neighboring cells were on an elevated surface, thus increasing the difference between a cell at the base of extruding features and its neighbors. Yet, of the map classified from the largest neighborhood size, 46374 m, smaller basins in the Gulf of Mexico were classified as flats, many canyon bottoms were classified as slopes, and the depression feature which categorizes the base of the Florida Escarpment was exaggerated in width (Appendix D). Therefore, the map created from the largest neighborhood was unsuitable.

Regions characterized by subtle differences in slope, such as the continental margin off the Carolinas, the Georges Bank off New England, and De Soto Valley off the Florida Panhandle, were not detected by any of the classification maps (Appendix D). These regions were misclassified as flat, while the bathymetry showed slight differences between adjacent areas. A few reasons may explain these classification errors. As De Rue and others (2013) pointed out, TPI was initially used for a study region composed of stark landform differences, without large swaths of gradual elevation change; yet for regions containing both prominent and gradual landforms, TPI was not able to recognize subtle elevation differences. This was the case for the Eastern U.S. EEZ, where there was pronounced and gradual elevation change. TPI was divided into discrete classes by its global standard deviation, which did not elucidate small changes in TPI at local scales.

Another issue that may account for blunders in classification was the coarse resolution of the GEBCO 19 DEM. Any elevation changes that occurred within a horizontal area less than the 464 m^2, the cell size of the DEM, went unnoticed. As previously stated, the GEBCO 19 grid was used for bathymetry data since it encompassed the Eastern U.S. EEZ. Although higher resolution data exists for parts of this region (Figure 4-3), much of the ocean has not been mapped in high detail, where researchers may need to use TPI for the sake of deep-sea coral habitat modeling.

Although one slope position map did not accurately reflect the entire Eastern U.S. EEZ, portions of each map well represented the topography of the seafloor, especially in regions of abrupt elevation change. An indisputable slope position or geomorphic feature map cannot be produced from DEM-derivatives due to idiomatic definitions of landforms and ambiguous transitions between landforms. However, using measures such as TPI and slope, semi-automated procedures can lead to rigorous yet efficient seafloor classification maps, which can be used toward deep-sea coral habitat modeling and conservation.

6.4 Summary

The results of enriching the Deep Sea Coral Research and Technology Program's deep-sea coral data with the WSGF set were presented. The Program can add this data to its online database for researchers to investigate relationships between deep-sea coral and seafloor geomorphology.

Results of classifying slope position zones within the Eastern U.S. EEZ were also presented. Areas of gradual elevation change were not accurately classified; however, regions of dramatic relief were well represented in the slope position maps. The efficient method of classifying slope position zones from TPI can be adopted by deep-sea coral habitat modelers to use in other regions.

Chapter 7 – Conclusions and Future Work

This chapter marks the end of the project. Section 7.1 provides a summary of the goals of the project, the process that was taken to achieve these goals, and how the products that resulted from this project were received by the client. Section 7.2 proposes subsequent projects to future GIS students who wish to improve our knowledge of deep-sea coral habitat preferences and geomorphic feature classification.

7.1 Summary and Conclusion

NOAA's Deep Sea Coral Research and Technology Program manages an online database containing georeferenced deep-sea coral data which the public can download. But it did not contain standardized information about which geomorphic feature each coral was located on. The goals of the project were twofold: (a) enrich the Deep Sea Coral Research and Technology Program's coral data with standardized geomorphic features, and (b) develop a seafloor slope classification scheme for the Eastern U.S. Exclusive Economic Zone (EEZ). Geomorphology is believed to have a profound impact on the distribution of deep-sea coral, and researchers can use coincident geomorphic information to study coral habitat preferences and develop more effective deep-sea coral conservation strategies.

Data which represented seafloor geomorphology had to have (a) worldwide coverage, (b) standardized feature categories, and (c) a licensing agreement allowing its derivatives to be redistributed and modified in any medium or format. The global seafloor geomorphic feature (GSGF) set created by Harris and others (2014) matched these criteria, so it was used to enrich the deep-sea coral data. The 24 separate features that made up the GSGF set were compounded into two features – base features and discrete features – using a spatial overlay function. A Python script was developed to combine the attributes to improve query speed, query capability, and to eliminate the effect of corals being accounted for more than once.

The GSGF were spatially joined to the deep-sea coral data to enrich each coral with information regarding which seafloor feature it was located on. No coral data was lost during the enrichment process, and a step-by-step instruction manual was written so the Deep Sea Coral Research and Technology Program can repeat the process when they receive more deep-sea coral data, which fulfilled the coral enrichment requirements.

To fulfill the second goal of the project, seafloor slope position zones were classified in the EEZ. Slope position was classified using topographic position, a popular semi-automated process which allows an analyst to define seafloor features in a timely manner for a specific geographic region and scale (Weiss, 2001). The map created from the largest neighborhood size was unsatisfactory; but maps created from the other four neighborhood sizes adequately represented the underlying bathymetry, except for regions of gradual elevation change. Researchers can adopt the methods presented in this report to classify seafloor slope position zones for other regions for the purpose of deep-sea coral habitat analysis.

The Deep Sea Coral Research and Technology Program plans to incorporate the GSGF data in its online data portal. Products created by this project can be used to further our understanding of deep-sea coral habitat preferences for conservation purposes.

7.2 Future Work

This project enriched data of the online National Deep-Sea Coral and Sponge Database with geomorphic feature attributes. However, attributes were added locally and not implemented online. Before the geomorphic feature attributes become available to online users, a query interface should be developed, especially for the decimal codes which represent discrete features. Such an interface would translate the decimal codes to the familiar name of each feature and allow users to query deep-sea coral records by the name of coincident geomorphic features.

For another future project, deep-sea coral data can be enriched with bottom current information. Three-dimensional ocean circulation models can be used to describe the interaction between current flow and seafloor topography; this interaction can be used to model deep-sea coral distribution.

We were unable to analyze the associations between deep-sea coral and seafloor geomorphic features because deep-sea coral was not randomly distributed, not independent of each other, and we were restricted to presence-only data. Future projects could design creative ways of removing such biases and quantify deep-sea coral's affinity for seafloor geomorphology, such as eliminating adjacent deep-sea coral points and using presence-only models (Guinotte et al., 2014).

Since the slope position maps produced in this study did not accurately classify regions of gradual elevation change in the Eastern U.S. EEZ, a future study could attempt to better classify those regions. An approach to overcome this shortcoming may be to split the Eastern U.S. EEZ into smaller zones containing regions of homogeneous elevation changes, or by using another metric, deviation from mean elevation, to classify slope position (Reu et al., 2012). Future projects could include other seafloor variables in their classification scheme, such as curvature, roughness, substrate material, or use different scales of topographic position index (TPI) to devise more intricate seafloor feature categories.

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Appendix A. Descriptions of Base GSGF Features (IHO, 2008 as cited in Harris et al., 2014).

Geomorphic Feature Category	Definition
Shelf	A zone adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths.
Slope	The deepening sea floor out from the shelf edge to the upper limit of the continental rise, or the point where there is a general decrease in steepness.
Abyss	Area of seafloor located at depths below the foot of the continental slope and above the depth of the hadal zone.
Hadal	Seafloor occurring at depths > 6000 m.

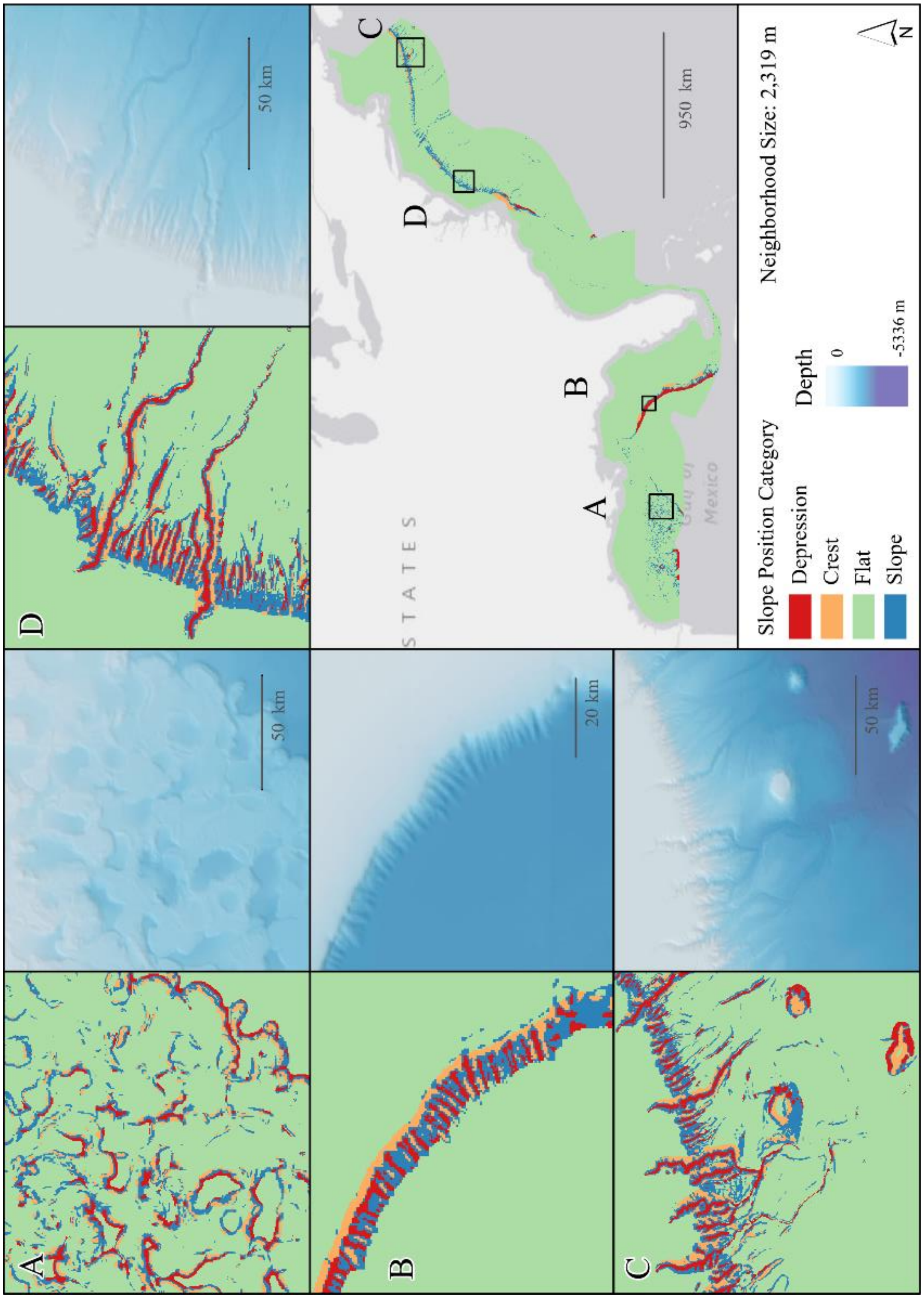
Appendix B. Descriptions of Base GSGF Features' Vertical Relief Classes (IHO, 2008 as cited in Harris et al., 2014).

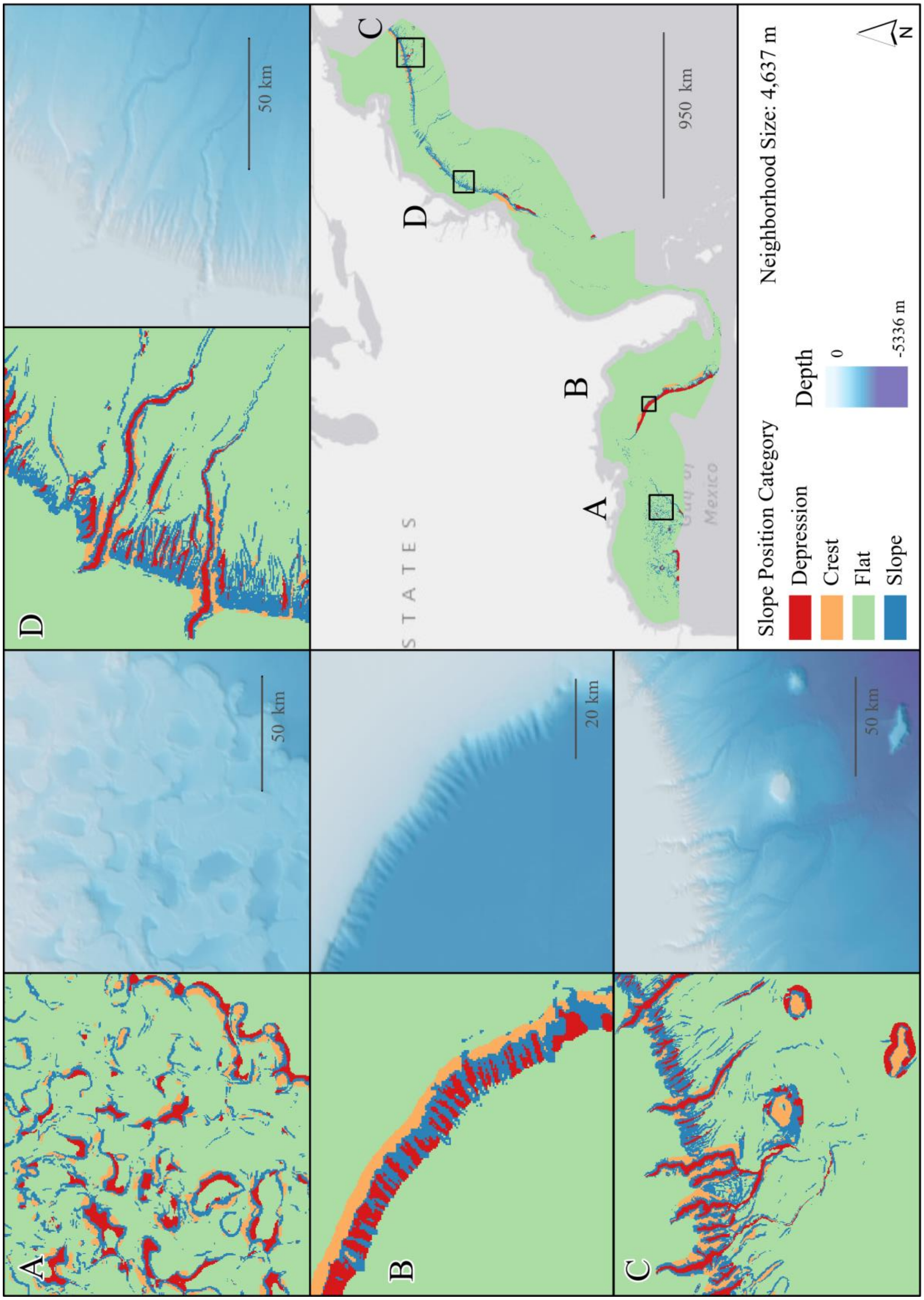
GSGF Relief Class Category	Definition
Abyssal Plains	Variation in relief less than 300 m.
Abyssal Hills	Variation in relief between 300 m and 1,000 m.
Abyssal Mountains	Variation in relief over 1,000 m.
Shelf – Low Profile	Variation in relief less than 10 m.
Shelf – Medium Profile	Variation in relief between 10 m and 50 m.
Shelf – High Profile	Variation in relief over 50 m.

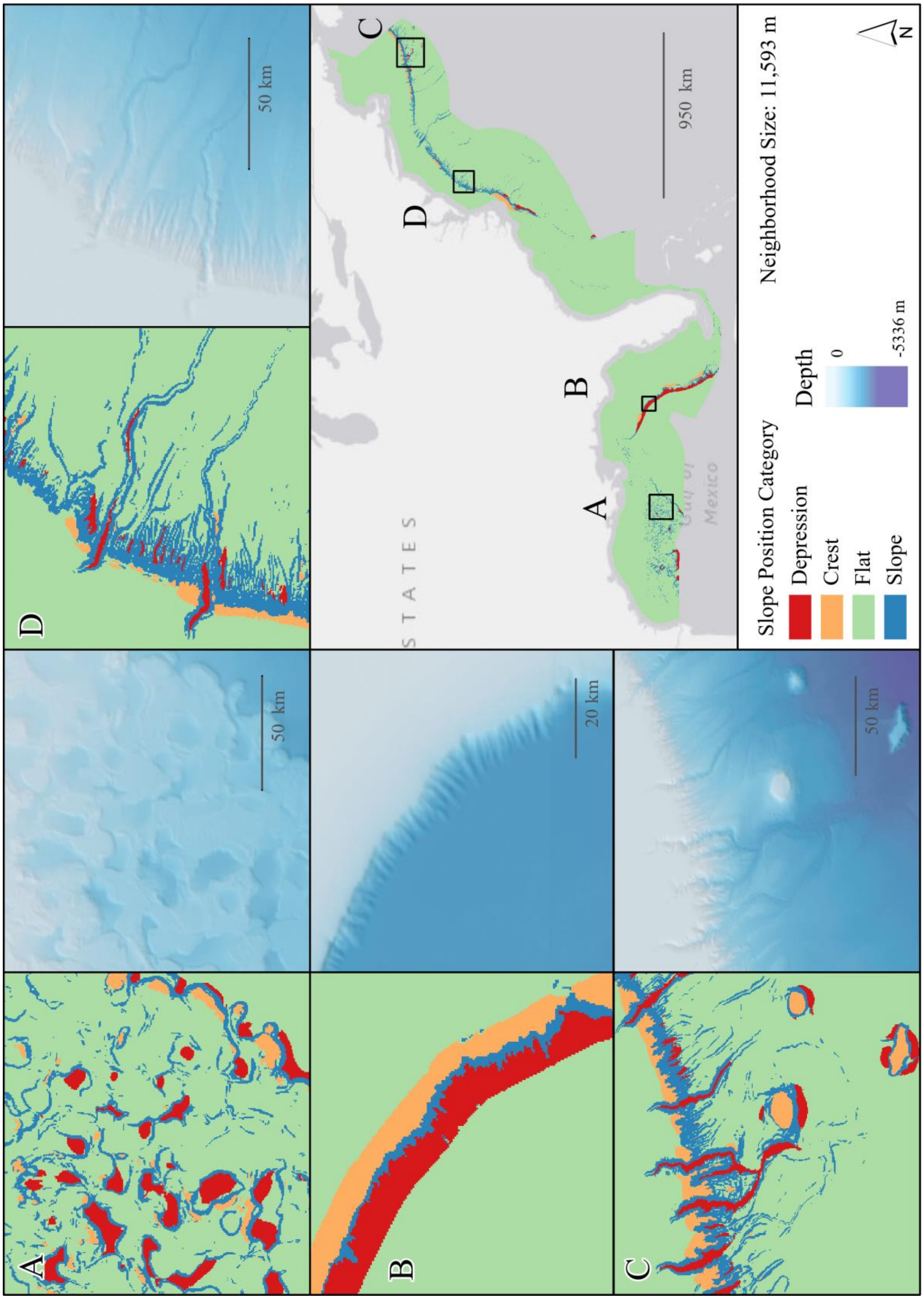
Appendix C. Descriptions of Base GSGF Discrete Features (IHO, 2008 as cited in Harris et al., 2014).

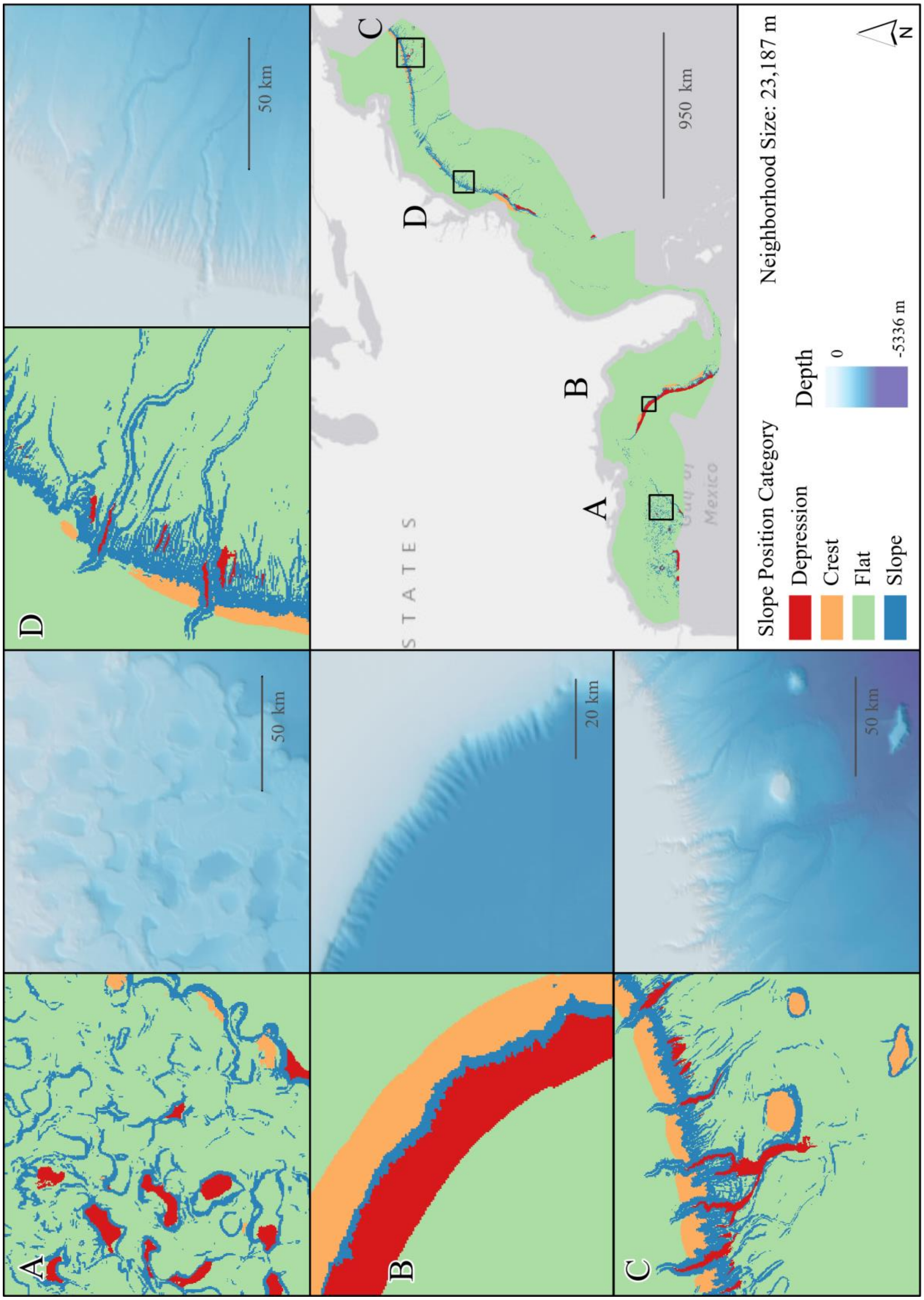
Geomorphic Feature Category	Definition
Basin	A depression equidimensional in plan and of variable extent defined by a closed depth contour.
Rise	A low gradient, evenly spaced, slope-parallel contours extending seawards from the foot of the continental slope generally confined to areas of sediment thickness >300 m.
Escarpment	An elongated, characteristically linear, steep slope >5º and areal extent of >100 km^2, separating horizontal or gently sloping sectors of the sea floor in non-shelf areas.
Plateau	A flat or nearly flat elevations of considerable areal extent, dropping off abruptly on one or more sides.
Ridge	An isolated (or group of) elongated (length/width ratio >2), narrow elevation(s) of varying complexity having steep sides, >1,000 m in vertical relief.
Fan	A relatively smooth, fan-like, depositional feature commonly found sloping away from the outer termination of a canyon or canyon system.
Seamount	A discrete (or group of) large isolated elevation(s) greater than 1000 m in relief of conical form.
Spreading Ridge	The linked, major mid-ocean mountain system of global extent coinciding with the youngest ocean crusts mapped by Müller et al. (1994).
Shelf Valley	Valleys incised more than 10 m into the continental shelf.
Glacial Trough	Elongate troughs, typically trending across the continental shelf, attributed to glacial erosion during the Pleistocene ice ages.
Canyon	Steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons and relief comparable to even the largest of land canyons.
Trough	A long depression of the seafloor characteristically flat bottomed and steep sided, generally open at one end
Terrace	An isolated (or group of) relatively flat horizontal or gently inclined surface(s), sometimes long and narrow, which is (are) bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.
Trench	A long narrow, characteristically very deep and asymmetrical depression of the sea floor, with relatively steep sides.
Guyot	A seamount having a flat top > 10 km^2 in areal extent and with a gradient of < 2º.
Rift valley	Valley confined to the central axis of mid-ocean spreading ridges; they are elongate, local depressions flanked generally on both sides by ridges.
Sill	A sea floor barrier of relatively shallow depth restricting water movement between basins.
Bridge	Features composed of blocks of material that partially infill trenches or troughs, forming a “bridge” across them.

Appendix D. Slope Position Zone Maps




A
B
C
D
50 km
20 km
50 km
50 km
950 km
STATES
Gulf of Mexico
Slope Position Category
Depression
Crest
Flat
Slope
Depth
0
-5336 m
Neighborhood Size: 4,637 m
N


A
B
C
D
50 km
50 km
20 km
50 km
950 km
STATES
Gulf of
Mexico
Slope Position Category
Depression
Crest
Flat
Slope
Depth
0
-5336 m
Neighborhood Size: 11,593 m
N


A
B
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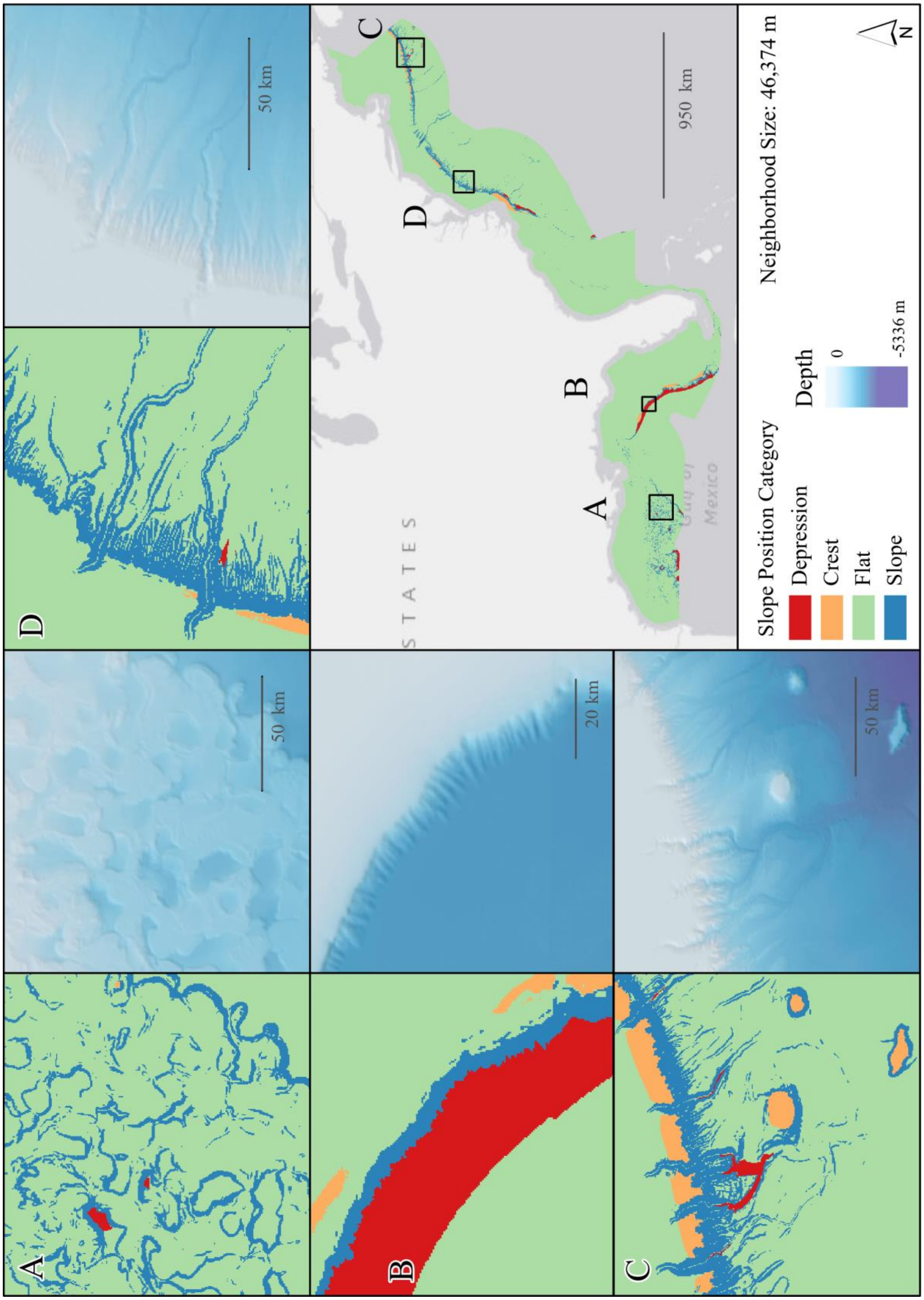
D
50 km
20 km
50 km
50 km
950 km
STATES
Mexico
Slope Position Category
Depression
Crest
Flat
Slope
Depth
0
-5336 m
Neighborhood Size: 23,187 m
N


A
B
C
D
50 km
50 km
20 km
50 km
950 km
STATES
Gulf of
Mexico
Slope Position Category
Depression
Crest
Flat
Slope
Depth
0
-5336 m
Neighborhood Size: 46,374 m
N